Automation of calibration of instruments in the excitation system of the generating units of Itaipu Binacional

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Abstract. This paper presents a system developed to automate voltage transducer calibrations used in the excitation system of the generating units at Itaipu Binacional. To improve efficiency and ease of operation, our system deploys multiplexed measurements to reduce the calibration runtime and is controlled by an application designed with Labview. After development, we validated the system through comparisons between manual and automated calibrations, performed with the assistance of the normalized error metric. Finally, the automatic calibration system brought greater standardization of procedures and up to a 65,7% reduction in the time spent on calibrations.

1. Introduction

The Itaipu power plant is considered the largest generator of clean and renewable energy on the planet. This title is the result of several factors, including the natural resources provided by the Paraná River and the management of the plant, which includes the experience and maintenance and operation planning of the generating units (GUs) [1]. In this context, one of the fundamental services to ensure the high quality, reliability, and operational efficiency of the GUs is the calibration of instruments used both in the control and operation of the GUs and during maintenance.

Calibration consists of comparing the measurement of a device under test (DUT) with a standard measurement system taken as a reference [2]. As a result, it is possible to obtain the measurement error of the DUT and the measurement uncertainty [3], representing the portion of doubt, meaning the quality of the calibration. Therefore, calibration is a fundamental tool for process quality, primordial for conformity checks or measurement corrections to maximize the accuracy of a measuring instrument. The calibration of instruments at Itaipu Binacional is carried out at the Laboratory Division (SMIL.DT) of the Maintenance Superintendence (SM.DT).

Despite the high excellence and performance achieved through the experience and maintenance planning of the GUs of Itaipu Binacional, there are still opportunities to enhance the quality and efficiency of processes. From this perspective, we developed an automated system for calibrating voltage transducers employed in the excitation system of the GUs of Itaipu Binacional. Calibrating such components is essential to ensure the performance, safety, and operation reliability of the GUs of Itaipu Binacional since the excitation system is essential to control the energy conversion of the machine and regulate reactive power on the grid [4]. Moreover, the developed system calibrates instruments simultaneously using measurement multiplexing to reduce the execution time and maximize service efficiency. Thus, the developed system brought numerous benefits, including service execution time reduction, improved reliability, standardization, and rework minimization, which can also be observed in other works such as [5], [6], [7], and [8].

The present work first describes the automated calibration system, discussing the measurement chain, calibration/adjustment of standard instruments, the calibration routine, and the developed application. Next, we present the main results, encompassing the system validation, and listing the gains achieved after its implementation. Finally, we offer conclusions, raising possible extensions of this work in the context of the Laboratory.

2. Automated Calibration System

This section introduces and discusses the developed automation system, presenting general aspects of the measurement system, calibration procedure, and the programmed application of automation. Before presenting and discussing the developed system, we introduce the instruments that the system can calibrate.

2.1. DUT

The DUTs handled by the automated system are DC voltage transducers used in the excitation system of the GUs at Itaipu Binacional, as shown in Figure 1. These transducers have continuous voltage inputs (-0,22~1,74 V; -0,18~1,68 V; -1~1 V; -2~2 V; 0~10 V), analog current outputs of 4~20 mA, and an accuracy class of 0.25 %.

Figure 1. Voltage transducers.

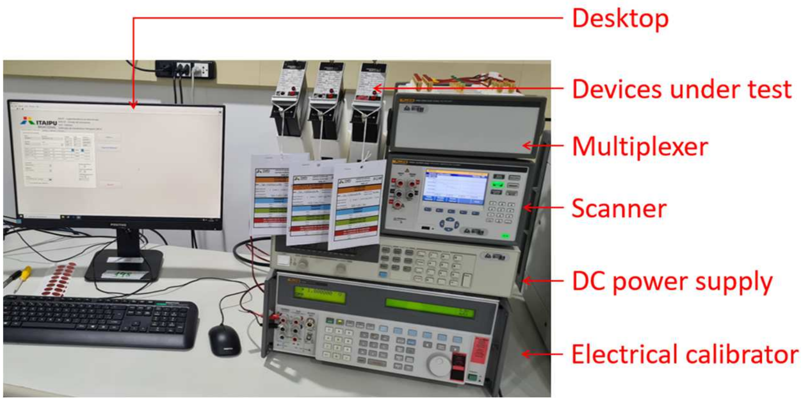

Figure 2. Complete Calibration system.

2.2. Automated System Overview

To provide an overview, Figure 2 shows the developed system in operation with all its components listed. In summary, multiple transducers are connected in parallel to an electrical calibrator and powered by a DC power supply. In addition, the input of the transducers is excited by an electrical calibrator, causing corresponding variations of the output currents, measured with the aid of a scanner. These instruments are controlled and coordinated by a desktop application developed by SMIL.DT, as shown in Figure 2.

To perform automated calibration, the calibration technician connects the transducers to be calibrated and inputs their data into the application. After completing these steps and running the application, the automated system calibrates the DUT autonomously. Throughout the process, the instrument control and measurement recording are carried out following a programmed procedure and without intervention from the calibration technician. At the end of the calibration, the application processes the collected data and issues calibration certificates based on the input data and calibration results. If the calibration detects

DUTs errors greater than their accuracy class, the calibration technician performs adjustments and repeats the automated calibration for those instruments. Finally, if the calibrated instruments are within their accuracy class, they are approved for use.

Figure 2 illustrates the system with three DUT. However, it is worth mentioning that the system is scalable. Since the multiplexer/scanner has 40 channels, the system could theoretically calibrate up to 40 DUTs simultaneously. In addition, the transducer mounting bases are also stackable and were fabricated of polyamide by a 3D printer. Therefore, more bases can be stacked, and more channels activated according to demand, increasing the system's capacity.

2.3. System Current Measurement Chain

The measurement chain of the system is illustrated in Figure 3. As presented previously, the calibrator excites the input of the transducers, generating a corresponding current signal I_n at the output of each transducer. As the system performs simultaneous calibration of transducers with the same voltage range, each transducer output is measured sequentially by the multiplexer and signal scanner. The multiplexing device alternates between measurement channels to obtain measurements from different sources using only one current meter.

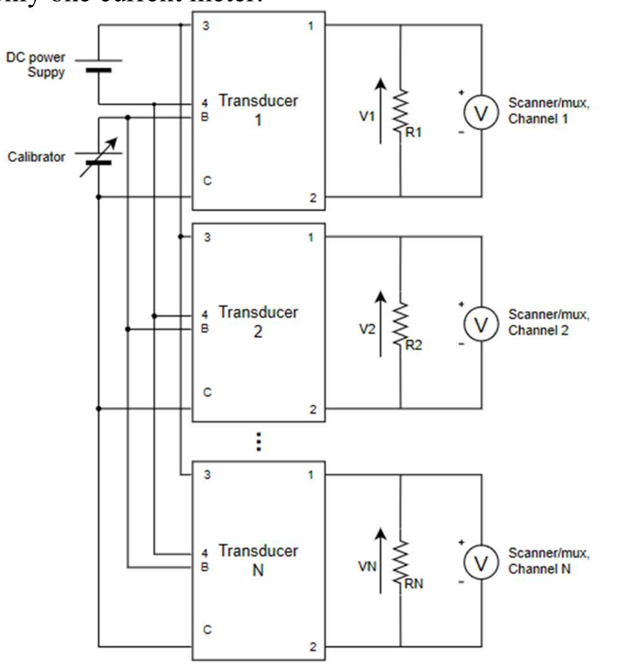

Figure 3. Measurement chain for calibrating $\boldsymbol{N}$ transducers.

Figure 4. PCB designed for shunt and scanner/multiplexer connection.

To take advantage of the available resources and assets, our automation setup deploys equipment and components already owned by Itaipu. However, our measurement system does not natively perform multiplexed current measurements. To circumvent this issue, high-precision and thermally stable $R_n = 100\,\Omega$ resistors were used as shunt elements for current measurements, as depicted in Figure 3. Therefore, the scanner and multiplexer perform multiplexed voltage measurements across the shunts, and the current is evaluated through Ohm's law [9]

$$I_n = \frac{V_n}{R_n} \,. \tag{1}$$

Since the scanner/multiplexer presents gold-plated 2 mm and mini-jack connections, we designed a printed-circuit-board (PCB) to connect the shunt elements, the scanner/multiplexer, and the current output of the DUTs. By deploying such PCBs, technicians can handle the instruments easily if transporting or periodic calibration of this setup is required. Figure 4 depicts the designed PCB and its connection in the measurement setup.

However, by deploying (1), the shunt accuracy limits the accuracy of current measurements. By analyzing the propagation of uncertainties [10] in this scenario, current measurement uncertainty under these conditions would be

$$u_I = \frac{1}{R + \alpha(T - T_0)} \sqrt{{u_V}^2 + I^2({u_R}^2 + \alpha^2 {u_T}^2)}\ , \tag{2}$$

where R is the nominal value of the shunt; α is the thermal drift of the shunt; T is the resistor temperature; T_0 is the reference temperature for thermal drift; u_V is the voltage measurement uncertainty performed by the scanner; I is the output current; u_R is the shunt tolerance; and u_T is the uncertainty of the ambient conditions.

By analyzing expression (2), the uncertainty of the shunt resistor (u_R) is the predominant factor, since the thermal drift (α) is low, calibrations are performed in temperature-controlled rooms, and the measurement uncertainty u_V is considerably lower than the other terms under the radical.

2.4. Adjustment and Calibration of the Multiplexed Current Measurement System

Despite being straightforward, equation (1) considers the nominal value of the shunt, limiting the measurement accuracy to the current shunt tolerance. Although the resistors adopted as shunts are high-precision components, their tolerances are high for metrological applications. This deficiency can be eliminated by performing a calibration adjustment in the measurement system.

As illustrated in Figure 5, the calibration curve adjustment of the system was performed with the aid of a standard electrical calibrator, which is the primary reference used in generating electrical quantities. For each channel, five current values were uniformly distributed along the 4~20 mA range using the electrical calibrator, and the voltages read on the scanner channels were measured. With the sets of pairs (V_n, I_n), linear regression was calculated using the method of least squares [4], i.e., the current of the n-th measurement channel is given by

$$I_n = A_n + B_n V_n\ , \tag{3}$$

where A_n is the correction factor for parasitic and thermoelectric voltages of the measurement circuit [11] of the nth channel; B_n is the estimated shunt conductance of the nth channel; and V_n is the voltage applied across the shunt of the nth channel. Table 1 presents the coefficients A_n and B_n for three channels, where it is possible to note that A_n has low values and B_n has values close to the nominal shunt conductance, that is, $1/R$.

Table 1. Curve calibration coefficients of the current measurement system.

n	A_n (S)	B_n (A)
1	-3,068658E-07	9,988600E-03
2	-3,225285E-07	9,989166E-03
3	-2,156574E-07	9,984274E-03

Although the differences between the estimations of equations (1) and (3) may seem negligible at first glance, the accuracy of the measurement is considerably improved through equation (3), as observed through calibration after curve fitting. Figure 6 exemplifies the system accuracy of a measurement channel (shunt-mux-scanner combination). In such a channel, the current measurement is very close to the current sourced by a standard calibrator, i.e., 8,3 ppm of difference. Therefore, after adjustments, the measurement system can achieve a performance compatible with off-the-shelf solutions such as 6.5-digit benchtop digital multimeters. However, it is noteworthy that not all 6.5-digit multimeters perform multiplexed current measurements.

2.5. *Calibration Routine*

Considering the measurement chain used, another crucial point for calibration is the definition of the calibration routine to be considered during the system programming. Figure 7 summarizes the calibration procedure used by the system. After starting the instrument calibration, an appropriate period is allowed for the instruments to reach their thermal stability. Next, the first voltage point to be calibrated is applied, requiring a new pause for the stabilization of the signal generated by the electrical calibrator. With the input signal stabilized, measurements are made on the output signals of the transducers sequentially with the aid of the multiplexer. The measurement of the transducer outputs is repeated until the configured number of readings is obtained for each calibration point. Then, the next voltage value to be calibrated is applied, and the process described so far is repeated until all the necessary readings for instrument calibration are obtained. Finally, with all the necessary measurements available, the data is processed, and the certificates are issued. It is worth noting that the uncertainty calculations and the issuance of certificates are automatically performed, according to calibration uncertainty analysis procedures already used in SMIL.DT and previously validated.

Figure 5. The arrangement used in the calibration and adjustment of the current measurement system.

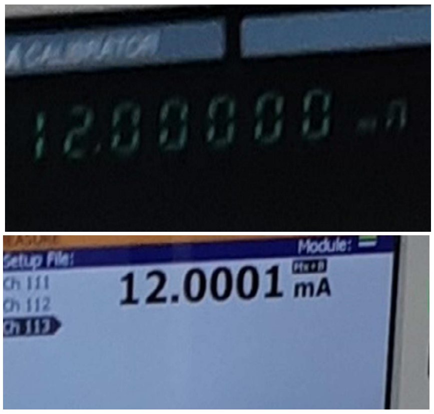

Figure 6. Comparison between current values indicated by the standard system (standard electrical calibrator) and the adjusted system (scanner and multiplexer).

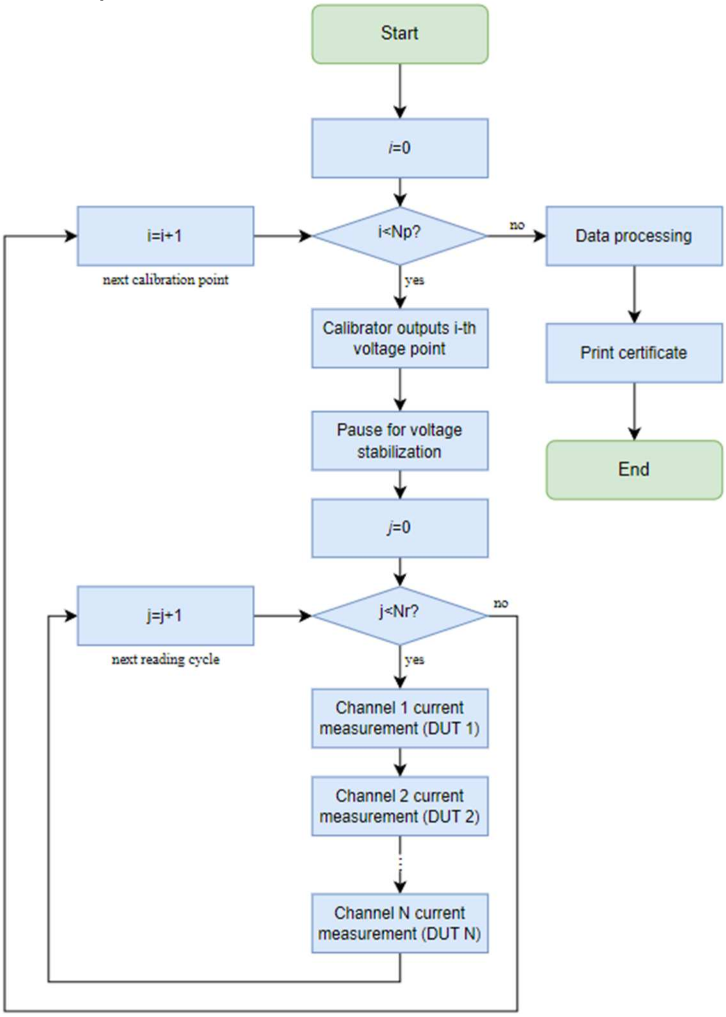

Figura 7. Simplified flow chart of the Calibration application.

2.6. *Application*

After defining the measurement configuration and calibration routine, we developed a Labview [12] desktop application to automate the process. Graphical programming language and the ability to control many bench instruments are desirable features of Labview. Aiming at a simplified operation and productivity increase, the application considered the needs and suggestions of calibration technicians of SMIL.DT. The application interface is divided into multiple tabs to improve organization and ease of operation, as shown in Figures 8, and 9.

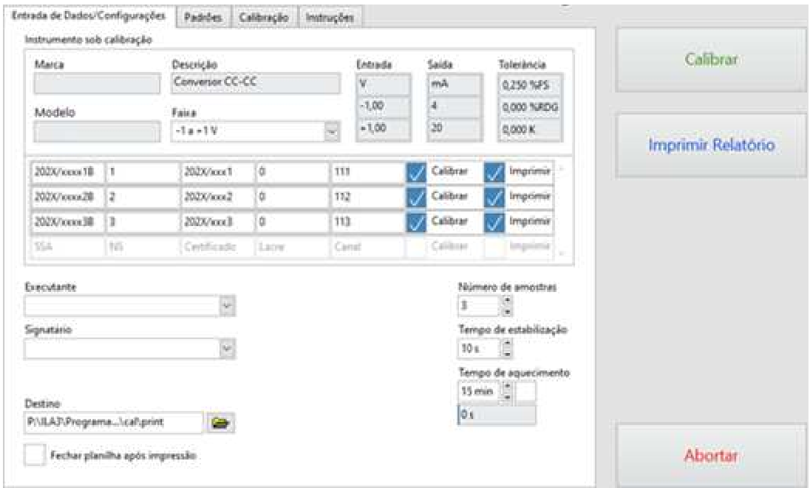

Figure 8. Application interface, data input and general configurations.

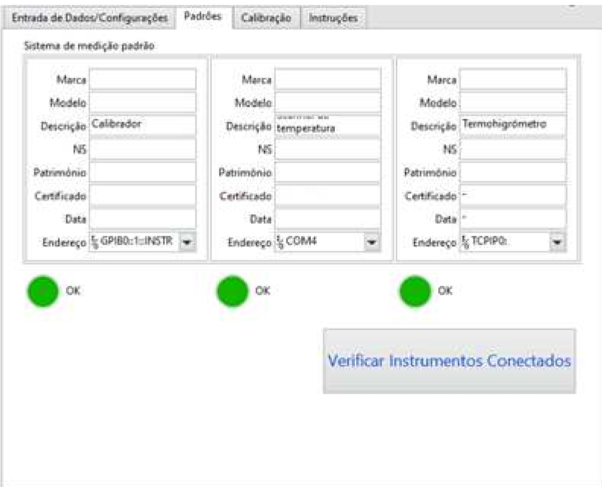

Figure 9. Application interface, standards tab

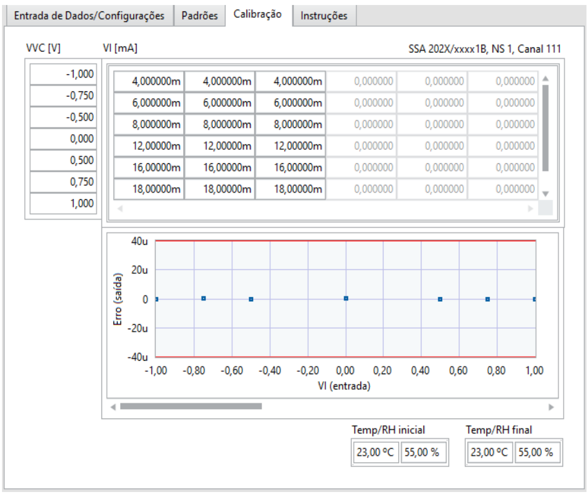

Figure 10. Application interface, calibration tab.

In the first tab, shown in Figure 8, the user enters calibration data and can adjust some settings. Initially, and most importantly, the transducer input range must be selected. The other parameters of the instrument under calibration are filled automatically to streamline the process. After this step, other data related to the calibrated instruments must be filled in, such as work order, serial number, certificate number, calibration seal to be placed, and the connected channel. In addition, the calibration executor and authorized laboratory signatory can be selected. Timing parameters for calibration can also be configured, as shown in the lower right corner of the first tab.

The second tab, shown in Figure 9, is responsible for verifying the standards to be used in calibration. The data filling of the standards is done automatically based on the serial number of the connected instrument. This is done by sending an identification request command to the connected instruments, which provide their respective data, including brand, model, and serial number. From this, the information is checked in a database, making it possible to automatically fill in the information of the second tab. Thus, the second tab helps the executor to verify if the standards are connected correctly and if they are calibrated within the validity period.

In the third tab, shown in Figure 10, the technician can monitor the calibration execution. Specifically, they can view the applied voltage values, current readings, and a transducer error graph, which helps to verify if the DUT error are within their tolerance, i.e., when the error (blue marker) does not exceed the instrument tolerance (red lines). Finally, the environmental conditions, i.e., temperature and relative humidity, are automatically collected from thermo-hygrometers installed throughout the calibration facility.

3. Results

This section presents the results obtained after the development of the automated calibration system, including system validation and the main benefits obtained after its implementation.

Initially, we validated the system to ensure its performance. The validation consisted of comparing calibrations performed by the automated system and by technicians at SMIL, both performed under the same conditions. Therefore, if the system presents results comparable to those already obtained in manual calibrations performed at SMIL, its performance can be considered satisfactory.

For numerical analysis, the normalized error calculation was adopted to evaluate the automated calibration method. The normalized error E_n is a metric of compatibility of different measurements [13], calculated through the expression [14]

$$E_n = \frac{|E_1 - E_2|}{\sqrt{U_1 + U_2}}, \tag{4}$$

where E_1 is the DUT error obtained by the automated calibration; E_2 is the DUT error for manual calibration; U_1 is the expanded uncertainty of the automated calibration; and U_2 is the expanded uncertainty of the manual calibration. If the normalized error is less than one, the measurements obtained by both methods are compatible.

To illustrate the comparison results, Figure 11 presents the automated and manual calibration results, showing the error of the calibrated instrument (y-axis) for each calibrated input value (x-axis). Furthermore, the input voltage values (V) were numerically converted to current (mA), making it possible to visualize the input and output data in the same unit of measurement. Visually, the results of automated and manual calibrations are very close, indicating equivalence between the methods. Numerically, Table 2 presents calibration results (error and uncertainty) and normalized error for each measurement point. Since the normalized errors in Table 2 are less than one, the measurements are compatible, validating the automated calibration method.

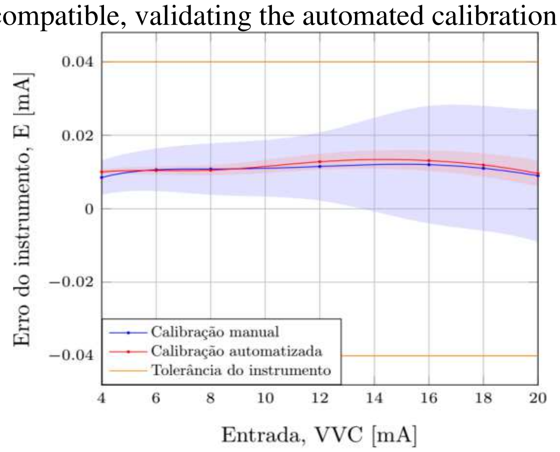

Figure 11. Comparison between the automated and manual calibrations.

VVC (mA)	Automated		Manual		E_n
	E_1 (mA)	U_1 (mA)	E_2 (mA)	U_2 (mA)	
4	0,0100	0,0007	0,0085	0,0047	0,32
6	0,0104	0,0011	0,0106	0,0058	0,030
8	0,0105	0,0014	0,0108	0,0070	0,042
12	0,0128	0,0022	0,0115	0,0093	0,14
16	0,0131	0,0028	0,012	0,016	0,068
18	0,0119	0,0032	0,011	0,017	0,052
20	0,0096	0,0035	0,009	0,018	0,033

Table 2. Comparison result of automated and manual Calibration.

Immediately after the system deployment, we observed a reduction in calibration runtime of approximately 65,7 % during scheduled GUs maintenances. However, one can notice that the runtime reduction is variable, as the GUs have different combinations of transducers. In addition, the calibration procedures were improved and fully standardized, given the systematization obtained by the developed application. Other benefits of calibration automation were also observed, including less rework in certificate issuance.

4. Conclusions

This work presented the automated system used to calibrate transducers of the excitation system of the GUs at Itaipu. The system was developed aiming at efficiency and ease of use, as we deployed available equipment and Labview for development. The efficiency of the system comes primarily by using multiplexed measurements, and automatic instrument operation and document issuance. After development, system validation was performed by evaluating the normalized error between automated and manual calibrations. Following the implementation and use of the developed system, calibration runtime experienced reduction and procedure standardization was improved. Finally, the experience obtained from the development of the system can be applied to other similar calibrations.

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