

Automation for calibrating a precision current source by Ohm's law method

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Received 17 October 2018; accepted 6 December 2019

We present the design of a program developed in LabVIEW for automating the calibration of a precision current source by the Ohm's law method. The program in addition to automating the instrument setup and measurement performs uncertainty computations in accordance with guide to the expression of uncertainty in measurement (GUM) and produces the calibration report and saves a record of the calibration process with all relevant information. The program has been tested for calibrating Keithley 6430 remote source meter in the current range of 1nA to 100 mA. While there are several benefits from the automation, but the most significant one is the achievement of low uncertainties in calibrating the current source.

Keywords: Current source, Automated calibration, Ohm's law method, Uncertainty, LabVIEW

1 Introduction

Measurement automation has been found very useful in laboratories for performing efficient and accurate measurements¹⁻¹² and it can be used with great advantage for the calibration of test and measuring instruments in metrology laboratories. The CSIR-National Physical Laboratory (CSIR-NPL), as the national measurement institute (NMI) of India, is providing measurement traceability to SI units to Indian industries, government organizations, R & D institutions, test and calibration laboratories and many others through calibration service. The LF, HF Impedance and DC metrology section at CSIR-NPL is providing calibration on several electrical parameters to many users that include industries, government organizations, R & D institutions, STQC laboratories and several others. In order to improve the quality, reliability and efficiency of our calibration service, we are implementing measurement automation in our calibration laboratory for the various electrical parameters. The basic difficulty in this endeavor is that an electrical calibration laboratory has to deal with calibration setups involving instruments made by different manufacturers and that ready to use software programs are not available for automating such customized calibration setups. Our approach to this

problem involves in developing our own automation programs according to the needs of the situation. In this paper we will describe an automation program which we have developed for the automated calibration of a precision current source in our laboratory.

A precision current source is one of the essential test and measuring instruments used in the electrical characterization of materials particularly in semiconductor industries and nanotechnology research. In order to ensure the accuracy of the current source it is necessary to calibrate it at periodic intervals. Calibration of the instrument is also a must for establishing the measurement traceability. It is always preferable to perform the calibration of a current source by automation since it can help in avoiding interference both from electrostatic noise and vibrations by virtue of avoiding operator presence and activities in the immediate vicinity of the setup. Electrostatic noise and vibrations are among the major sources of error that can vitiate any low current measurement¹³. The efficacy of the automated calibration process would depend on the availability of the right kind of calibration software with the required features. In order to meet this requirement, we have developed a versatile calibration program using the LabVIEW platform. This program has been designed to automatically perform all the functions related

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to the calibration process including uncertainty computations and calibration report generation.

2 Calibration System

In order to establish measurement traceability, current calibration is normally done by the Ohm's law method¹⁴. In this method the current is measured by the voltage developed across a standard resistance making the calibration traceable to the primary standards of voltage and resistance, viz., the Josephson array voltage standard (JAVS) and quantum hall resistance (QHR) standard. The current source we have chosen for calibration is the Keithley 6430 remote source meter. This instrument belongs to the category of source-measure units (SMU) which can be programmed to source either voltage or current and also to measure them¹⁵. Basically this is a very high precision instrument extensively used in the testing and electrical characterisation of semiconductors, solar cells, nanomaterials etc. As a current source, it can source currents from ± 0.5 fA to ± 105 mA, but Ohm's law method is not very accurate for calibrating currents below nano amperes. Therefore, in this work we are not proposing the calibration system for currents below the nanoampere range. We have designed the calibration set up consisting of set of metrology grade standard resistors of known high accuracy and a standard DMM, Fluke 8508A 8.5-digit reference multimeter, for measuring the voltage with very high precision and accuracy. Figure 1 shows the block schematic of the measurement setup. Both Keithley 6430 and Fluke 8508A are controlled from a personal computer (PC) through GPIB interfacing with the software written in LabVIEW. An ordinary PC can meet the requirements of this automation job.

3 Uncertainty Parameters in the Current Source Calibration

The current to be calibrated (I) is passed through a calibrated standard resistance (R) and the voltage developed (V) across the resistance is measured and the current is obtained as $I = V/R$. The primary calibration data is the voltage measured. It is necessary to follow careful procedure for estimation of uncertainty using the calibration data and instrument specifications and it is imperative that this should be done according to *GUM* guidelines which are universally followed. *GUM* provides clear guidelines on how to evaluate the individual uncertainty components where the uncertainty components are to be calculated as

statistical variances¹⁶. Following the method described in *GUM*, the first step in calculating the uncertainty is calculating Type A and Type B standard uncertainties.

Type A uncertainty u_a (also called repeatability uncertainty) is obtained directly from the measured data as the estimated standard deviation of the mean defined as $u_a = \frac{\sigma}{\sqrt{n}}$ where, σ is the standard deviation

of the sample and n is the number of measured data points in the sample. Estimation of type B uncertainty components needs input parameters and they have to be identified based on the various factors that influence the measurement. In the present case, we have to consider uncertainty contributions due to the DMM, the standard resistor and the current source. To convert the uncertainty contributions due to V and R into units of I , we have to find their sensitivity coefficients using the functional relationship between these three quantities.

As $I = \frac{V}{R}$, a very small error δI in I due to very small errors δV in V and δR in R can be obtained as:

$$\delta I = \frac{1}{R} \delta V - \frac{V}{R^2} \delta R = C_1 \delta V + C_2 \delta R \quad \dots (1)$$

In (1), C_1 and C_2 are the sensitivity coefficients for the uncertainty components due to V and R , respectively. To convert their uncertainty contributions into standard deviations we have to know the type of probability distribution function each uncertainty follows which will tell the divisor to convert the uncertainty to standard deviation. The important sources of uncertainty are the ones listed in Table 1.

In the measuring system there are some other error sources also, like offset errors and thermoelectric emf due to connections made with dissimilar metals, but they can be minimized or eliminated by correct

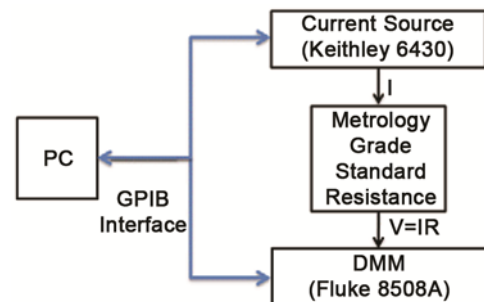


Fig. 1 – Block schematic of automation setup for current source calibration.

Table 1 – Listing of Type B uncertainty components in current source calibration.

Uncertainty component	Source of uncertainty	Uncertainty parameter	Sensitivity coefficient	Probability distribution & divisor	Standard uncertainty
U_{b1}	Voltage reading by DMM	$\delta V1$	C_1	Normal, 2	$\delta V1 \times C_1 / 2$
U_{b2}	DMM range	$\delta V2$	C_1	Rectangular, 1.732	$\delta V2 \times C_1 / 1.732$
U_{b3}	Value of standard resistance	$\delta R1$	C_2	Normal, 2	$\delta R1 \times C_2 / 2$
U_{b4}	Resistance variation due to temperature	$\delta R2$	C_2	Rectangular, 1.732	$\delta R2 \times C_2 / 1.732$
U_{b5}	Drift in resistance since last calibration	$\delta R3$	C_2	Rectangular, 1.732	$\delta R3 \times C_2 / 1.732$
U_{b6}	Current source resolution	I_{Res}	1	Triangular, 3.464	$I_{Res} / 3.464$

working practices, so they have not been included in the uncertainty analysis. Essentially unwanted offset voltages can be cancelled out by making two measurements, one with current of one polarity followed by current of the same magnitude but of the reverse polarity and then taking the average of the two measurements¹⁵. In our measurements we have adopted this method and the software has been designed to take care of this automatically.

The Type B uncertainty parameters are obtained from the calibration certificates and specification manuals of the DMM, standard resistors and the current source. Once the magnitudes of all the relevant uncertainty sources are estimated they can be combined to obtain the probable estimate of the total measurement uncertainty, called the combined measurement uncertainty U_C . The individual uncertainty components are combined by the root-sum-square method as given by Eq. (2).

$$U_C = \sqrt{U_a^2 + U_{b1}^2 + U_{b2}^2 + U_{b3}^2 + U_{b4}^2 + U_{b5}^2 + U_{b6}^2} \quad \dots (2)$$

The final step in the uncertainty evaluation is calculating the expanded uncertainty. The expanded uncertainty U is specified as the product of the combined uncertainty U_C and coverage factor k ($U = U_C \times k$) which will tell the confidence level with which the uncertainty is reported. The coverage factor is decided by the type of probability distribution which U_C follows and to know that it is necessary to determine the effective degree of freedom of U_C . Assuming that the combined uncertainty is a linear combination of independent sample variances, the effective degree of freedom can be determined using the Welch-Satterthwaite formula. According to normal procedure, for an effective degree of freedom of 50 and higher, we can assume the uncertainty to be normally distributed and $k=2$ for a confidence level of

approximately 95 %. For a value lower than 50 for the effective degree of freedom, the method followed is to assume a probability function represented by a student-t distribution and use the student coefficient corresponding to the effective degree of freedom to find the value of k for the desired confidence level.

4 Calibration Software Design Requirements

For automating the calibration of the current source by Ohm’s law method, the important functions the software has to perform are:

- (i) opening communication between PC and the two instruments, configure Keithley 6430 as current source, Fluke 8508A for voltage measurement,
- (ii) setting experimental parameters, delay times and input variables for performing the measurement,
- (iii) acquire the measurement data and save into a file,
- (iv) compute uncertainty and
- (v) generate an inventory of the calibration and save file

The automation program follows the designed procedures outlined by the flowchart shown in Fig. 2. The program can be divided into two parts, one part for automating the instrument operations for conducting the measurement and the other for the estimation of measurement uncertainty and report generation.

5 Program Description

We have used LabVIEW for creating the automation software because LabVIEW provides all the necessary tools for carrying out the required operations. LabVIEW is a software development platform created by National Instruments with emphasis on scientific and engineering applications¹⁷. It is a graphical programming language that uses icons instead of text codes which has many advantages over conventional text based languages. LabVIEW has found extensive use in automatic

control of laboratory measurements for which numerous references can be found in the literature. The functions in LabVIEW are known as virtual instruments or VIs. As instrument drivers of both Keithley 6430 and Fluke 8508A are available in LabVIEW, we can develop the application program without learning the elaborate programming protocol for these instruments. With the VISA VIs in LabVIEW, it is only necessary to know the SCPI (Standard commands for programmable instruments) commands to program these instruments. SCPI commands are in the form of ASCII strings which are available in the instrument manuals and it is very easy to send these commands to the instruments from LabVIEW using the VISA VIs.

5.1 Measurement automation

For calibrating the current source, it is normal to take sets of data by repeat measurements made over a period of several days. This is for ensuring that the measuring system would encounter the full range of all likely measurement conditions and to establish the consistency and repeatability of the measurements. Accordingly, the program is designed for performing uncertainty calculation based on repeated measurements spread over as many days as needed where we save individual day's data into the same spreadsheet file created at the beginning specifically for this purpose. Referring to the flowchart in Fig. 2, the program creates a new file for saving the measurement data in a spreadsheet format at the beginning of the calibration process. For the same set of measurement on subsequent times the program begins by opening the data file saved during the previous measurement. Once a predetermined number of data points are collected the file is updated by adding the newly measured data as a new column in the spreadsheet. The LabVIEW code made for this is shown in Fig. 3.

Instrument automation begins with establishing communication between the PC and the instruments by opening VISA sessions for both the instruments and configuring Keithley 6430 as current source and Fluke 8508 A for voltage measurements. The instrument parameters are set by sending the required SCPI commands. The main current source setting is selection of current range and resolution. The DMM is set for auto-ranging and 7.5-digit resolution. The VISA Write VI is used for sending the commands from the PC to instruments and VISA Read VI for receiving the response from the instruments. After the

instruments are configured, it is necessary to define the experimental parameters to control the measurement with the application software. The data acquisition part of the program is designed to run in a FOR loop to continuously measure as many data

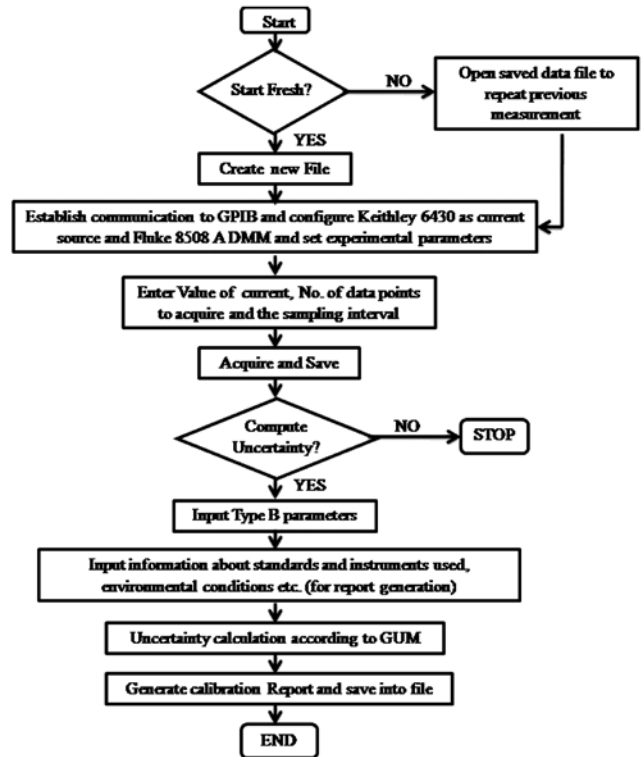


Fig. 2 – Flow chart of automation program for current source calibration.

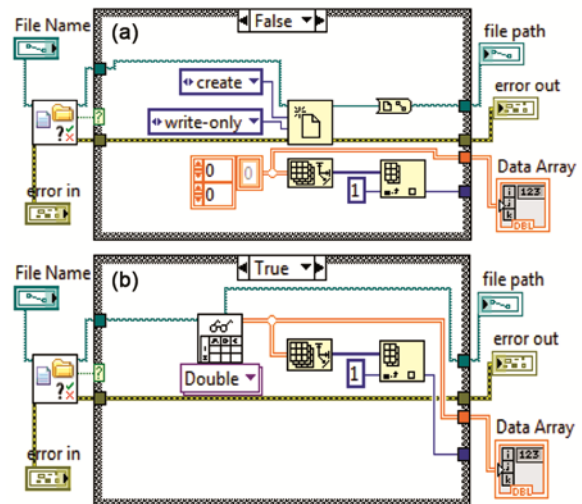


Fig. 3 – LabVIEW code segment for (a) creating a new spreadsheet at the start of the calibration process and saving the data and (b) opening the already existing spreadsheet for adding fresh set of data on subsequent measurements. The file with new data added will be saved at the end of the measurement.

points as needed. Before the measurement, value of the current to be sourced by Keithley 6430, the loop iteration number and data acquisition rate by DMM are to be set. As they are variables that can vary from measurement to measurement, they have been designed as controls on LabVIEW front panel. By defining the variables as controls, the operator can decide their values as required and input them accordingly at the time of program execution. The FOR loop iteration number determines the number of data points acquired in one measurement cycle and the loop delay time determines the data sample time. By repeatedly reading the DMM in the FOR loop a complete set of data is collected and saved into the file. To take care of instrument response time requirements, time delays have been added as required using the time delay VI. The data are acquired without any operator bias and that all data points acquired are equally spaced in time and it maintains the consistency of the data acquisition process. The front panel of the program incorporates both graphical and numerical displays for viewing the measurement data. The display on the computer screen is helpful for real-time measurement monitoring and checking the results.

5.2 Uncertainty computation and documentation

After acquiring the required amount of data, the program can proceed for uncertainty computation. Uncertainty calculations involve component by component evaluation of both Type A and Type B standard uncertainties. Type A evaluation involves processing the measured data stored in the data file and this is done in a very few steps using functions available in LabVIEW. The operations involve reading the data into an array, then averaging each set of measurement, apply offset corrections, converting

the voltage value into current using the standard resistance value, and estimate the Type A standard uncertainty from the variance. Estimation of Type B uncertainties needs input from outside. These are the uncertainty components listed in Table 1 and it is very convenient to input all of them using the Table control VI in LabVIEW. All mathematical computations are done using the formula node VI. This involves computing discrete equations to get the standard uncertainty components, combined uncertainty and effective degree of freedom. Figure. 4 shows the LabVIEW code used for the uncertainty computation. The Formula Node in the LabVIEW is a convenient, text-based node which allows entering multiple algebraic formulas directly into the block diagram in C - syntax and makes it easy to perform complex mathematical operations on the block diagram.

As explained earlier, the effective degree of freedom is used to find the coverage factor for the expanded uncertainty from Student coefficients. In order to do this the program uses stored values of t-distribution to assign the value of *k* corresponding to the effective degree of freedom.

We have developed the program for the complete automation of the calibration process which includes real-time report generation of the calibration process using the Microsoft office report generation tools in LabVIEW. The programming is done to generate the report with all relevant information such as the model and serial number of the device under calibration (DUC), model and serial numbers of the standards for their traceability record, environmental conditions, and calibration dates and data file details. These parameters are directly input into the program using the Table Control VI so that they can be saved in the report generation file. The report also includes the measurement results, all uncertainty input parameters

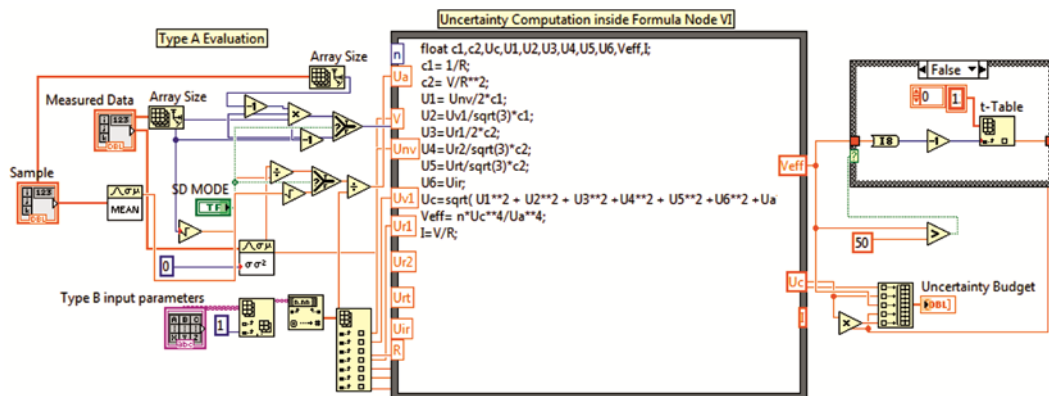


Fig. 4 – LabVIEW code for uncertainty computations.

and uncertainty results of the DUC. Figure 5 shows a front panel display for this program segment. By including the measured data and uncertainty input parameters in the report, we can always verify the uncertainty results independently, if needed. All the report contents are formatted to appear under relevant headings in tabular form so that they can be easily understood and analysed. At the end the report with all the relevant information is saved into an MS Word file to have proper documentation of the calibration performed and can be easily accessed whenever needed.

6 Measurement and Results

We have implemented the automation set up with the LabVIEW program to perform the calibration of Keithley 6430 as a current source. The calibration system as described in Section II was set up in an

environmentally controlled laboratory room. The room temperature and relative humidity were contained well within $(24.5 \pm 1)^\circ\text{C}$ and $(50 \pm 10)\%$, respectively. The measurement set up incorporated in its design provisions for proper shielding and guarding of sensitive circuits parts to enable accurate current measurements down to nanoamperes. The current source has been calibrated for currents in the range of 1 nA to 100 mA. After the system was set up measurements were performed automatically and the calibration reports were generated by the automation software described in the previous section. Operator intervention is required only when it is needed to change the standard resistors as required for the current to be calibrated. The uncertainty results are tabulated in Table 2.

As mentioned earlier, the calibration program has the option to run for acquiring data only or acquire data

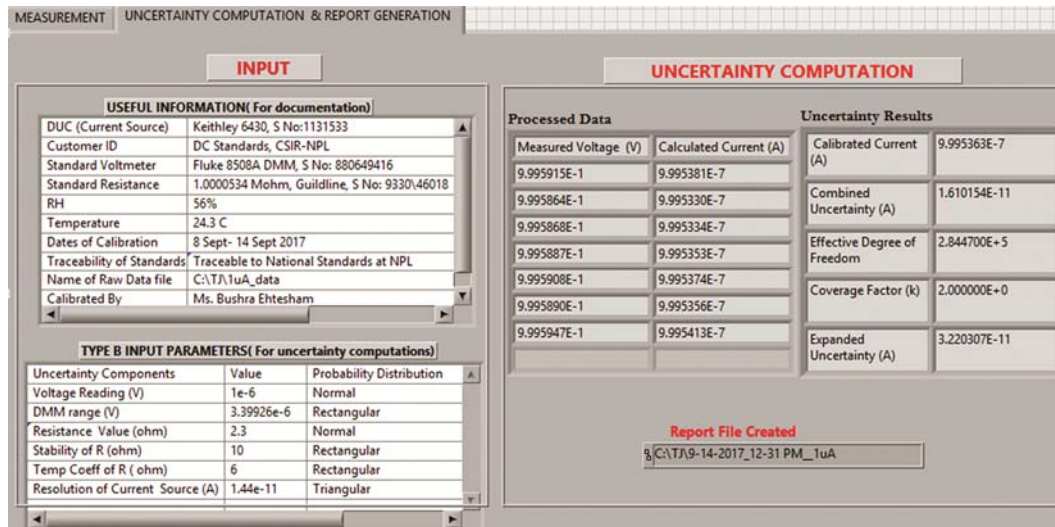


Fig. 5 – Snapshot of front panel of LabVIEW program showing inputting of parameters for uncertainty computation and report generation using Table Control VI on the left half. The right side shows the results of uncertainty computation. The contents on this screen will be saved into the report generation file created at the end of the calibration along with other relevant details.

Table 2 – Consolidated results of calibration.

Programmed Current	Source-meter Reading (offset corrected)	Calibrated Value	Standard Resistance	Expanded Uncertainty (\pm)	Coverage factor (k) for 95 % confidence level
1 nA	1.00001 nA	0.999673 nA	10 M Ω	114 fA	2.2
10 nA	10.0001 nA	9.998031 nA	10 M Ω	1.08 pA	2.2
100 nA	100.001 nA	99.97204 nA	10 M Ω	10.8 pA	2.2
1 μ A	1.00001 μ A	0.9995363 μ A	1 M Ω	32.203 pA	2
10 μ A	10.0001 μ A	9.996168 μ A	100 k Ω	318.03 pA	2
100 μ A	100.001 μ A	99.96717 μ A	100 k Ω	3.109 nA	2
1 mA	1.00000 mA	0.999849 mA	100 Ω	30.314 nA	2
10 mA	10.00025 mA	9.989977 mA	100 Ω	302.815 nA	2
100 mA	100.0025 mA	98.559 mA	10 Ω	3.025 μ A	2

and compute uncertainty simultaneously. The first option allows acquiring multiple set of data before going for uncertainty computation. When uncertainty is estimated using multiple set of data, the type A uncertainty is determined from the standard deviation of the samples mean. The results presented in Table 2 are obtained using 7 sets of measurement for each calibration point performed over a period of 7 days.

7 Conclusions

In our laboratory we have automated the calibration of the current source using program developed in LabVIEW. The program has been tested for calibrating Keithley 6430 remote source meter as a current source in the range of 1 nA to 100 mA and it has been found very efficient and reliable. Automation has greatly reduced the effort required to perform the calibration. However, the most important benefit from automation lies in achieving much lower calibration uncertainties compared with previous calibrations of the same instrument done manually. The document file created at the end of the calibration provides a permanent record of the calibration for any future reference.

As SCPI commands are standardized for basic functions for a large number of test and measuring instruments, a program developed for one instrument can be made to work with many other instruments also. Therefore, the programming steps presented here could be easily adapted with minimum modifications for the automation of several other similar instruments also. One major advantage of using LabVIEW is that it is very easy to reconfigure a program made in LabVIEW and this could be very helpful if we want to modify the program to automate another similar instrument in a very short time. The program that we have presented is very easily modifiable and expandable by adding more functions and analysis as and when required.

Acknowledgement

The authors thank Mr Harish Kumar and Mrs Poonam Sethi Bist for technical support. The authors are grateful to Dr D K Aswal, Director, CSIR-NPL and Dr V N Ojha, Head, TFEEM Division for their guidance and encouragement.

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