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Design of Virtual Reference Standard for Calibration in University Education

Zivko Kokolanski and Petar Vidoevski

Abstract - The paper elaborates the design and implementation of a low-cost virtual reference standard for teaching calibration principles in metrology in higher education. Two major aspects have been analysed: the virtual instrument architecture, and metrological evaluation of the proposed solution consisting of a virtual instrument and power amplifier. It has been shown that the applied programming architecture allows implementation of most functionalities provided by the modern calibration instruments, which can be further exploited in the University education laboratory practice. The obtained experimental results suggest that the system offers good stability and low non-linearity, which can be used for calibration of low to medium-accuracy instruments, and for teaching metrology in higher education. Besides the virtual reference standard, the metrological performances of the power amplifier are also analysed.

Keywords - calibration; LabVIEW; power amplifier; virtual instrument.

I. Introduction

Metrology is the science of measurements and its application in all areas of industry and everyday life [1]. One can easily say that without the development of metrology, progress in science and modern life can be hardly imagined. However, despite its undoubted technological, economic, scientific and social significance, there is a lack of teaching content in metrology in the higher education [2]. This is especially important if we emphasize that metrology is a multidisciplinary science and it covers different educational profiles. One of the basic prerequisites that should be provided for proper implementation of metrology in higher education is laboratory instrumentation. On the other hand, the high-accuracy instrumentation commonly used in the metrological laboratories is quite expensive and often inaccessible to universities, especially considering that for good transfer of knowledge an individual laboratory approach to students must be applied. Therefore, the educational practices of metrology in the university education are often too theoretical or significantly differ from those in the industry.

One approach that can contribute to overcoming the above mentioned challenges is the application of virtual instrumentation. Namely, virtual instruments enable the development of software-defined instrumentation with easy-to-define functional and metrological performances. Instruments developed in this way are significantly cheaper than classical instruments and provide great flexibility, which is crucial for their application in the University education. The user interface and the operation of virtual instruments can be developed in accordance to the professional equipment used in the calibration laboratories. In this way, efficient and high-quality laboratory practice can be provided to higher education students. This paper aims to propose the design and implementation of a virtual reference standard for electrical quantities.

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A lot of scientific papers on using virtual instrumentation in the field of metrology have being published. Authors in [3] propose a virtual instrument for automatic control and calibration of electrical reference standards. Similarly, [4] proposes a remote calibration system by using virtual instrumentation, whereas [5] elaborates an automated system for multimeter calibration in LabVIEW. There are also papers on using virtual instrumentation for calibration of Data Acquisition (DAQ) systems for rocket propulsion test facilities [6], and on-site calibration systems for electronic instrument transformers [7]. However such approaches doesn't eliminate the need of realistic reference standards and instruments to be exploited in the university education.

This paper proposes a complete hardware and software solution of a low-cost virtual reference standard for electrical quantities [8] with improved accuracy. Two aspects are covered in the paper: the instrument design and implementation, and metrological evaluation. In order to extend the output signal levels of the virtual instrument, an external power amplifier [9] is used. The broader scope of such virtual reference standard is its integration into remote virtual laboratory, which will be considered in future publication.

II. Virtual reference standard design

The virtual reference standard (calibrator) for electrical quantities consists of several functional modules: PC-based virtual instrument, data acquisition card, power amplifier and device under test (DUT). The simplified block-diagram of the system is given in Fig.1.

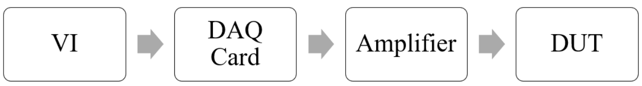

Fig. 1. Simplified diagram of virtual standard for electrical quantities

The virtual instrument (VI) is a specialized software program running on a personal computer (PC) which provides all user and system functionalities. In general, the VI processes the user interactions with the graphical user interface and reproduces the appropriate electrical signals with a data acquisition card. In order to obtain a higher amplitude, the output signal generated by the DAQ card is amplified with a specialized power amplifier. Such a signal can be finally used to test a device (DUT) or calibrate an instrument used to measure given electrical quantity.

B. Virtual instrument implementation

The front panel of the virtual instrument given in Fig. 2 consists of several parts: two text indicators for specific user-related messages, connection terminals realized as a logical indicators glowing according to the defined electrical quantity, keyboard for setting all system and functional parameters, potentiometer for changing the signal amplitude, and a power button. In general, the calibrator operates in two modes: standby or operate. The transition between the standby and the operate mode is possible by pressing the corresponding keys on the VI's front panel. In the standby mode, the user actions are related to setting the signal parameters. The text indicator on the left side in Fig.2 is used to show the signal parameters, the mode of operation, and message whether the generated voltage is dangerous. The indicator on the right hand side shows the current value entered on the keyboard, a reminder to enter the measurement unit, and whether a decimal or integer part is entered. Additionally, by pressing the setup key in the standby mode, the user can modify additional signal parameters such as: wave shape, offset, phase shift, etc. On the other hand, the operate mode is used to generate the signal according to the predefined parameters. The user can use the potentiometer to modify the signal value in real-time when the calculated relative error will be displayed on the text indicator on the right hand side. It is important to note that the signal parameters cannot be modified in the operate mode. However, by pressing the save button, the user can record the calibration results into comma separated values or configuration file.

The block-diagram of the virtual instrument is given in Fig. 3. In order to have low dependence on other modules, and high cohesion, the program is organized into three iterative loops. The first is the producer loop in which events are generated, and based on those events data is fed into a specific buffer.

The second loop is responsible for the main operation of the virtual calibrator, i.e. initialization of default values, switching to operating mode, message display, and signal parametrization. The third loop is related to the data acquisition, i.e. it generates messages to start/stop the acquisition and generate a signal.

The virtual calibrator loop consists of five states. At the beginning, the program is in an initialization state where the controls, indicators, and global function variables are initialized. Afterwards, the program enters into idle state and waits for the power up button to be pressed, which initiates the standby state given in Fig. 4. The virtual instrument now reads the data from the functional global variables in which the signal values are stored, the values entered from the keyboard, as well as handles certain messages. The "operate" state reads the function global variable for the signal parameters, the function global variable for error calculation, as well as the voltage and current check. Next, the value of the signal is sent through a special buffer in the signal generation loop. When switching from operate to standby in the third loop, a message that the acquisition will stop is generated. In the "end" state, the variant buffer is read and the virtual calibrator shuts down. Two types of messages are possible, one stating that an error has occurred, or that the program has finished normally by pressing the power up button.

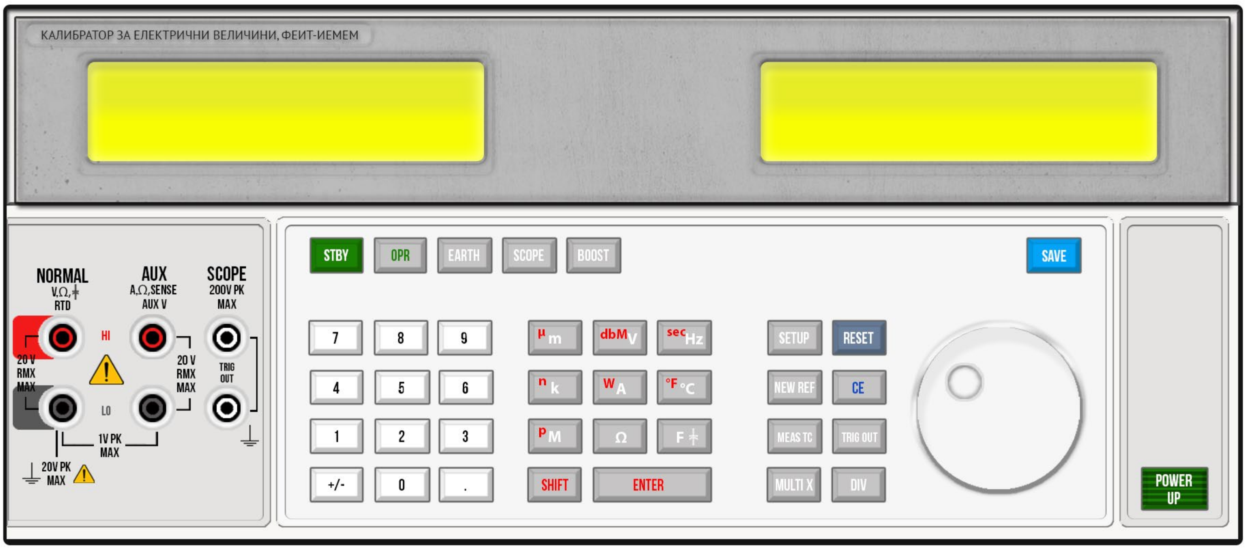

Fig. 2. Front panel of the virtual calibrator for electrical quantities

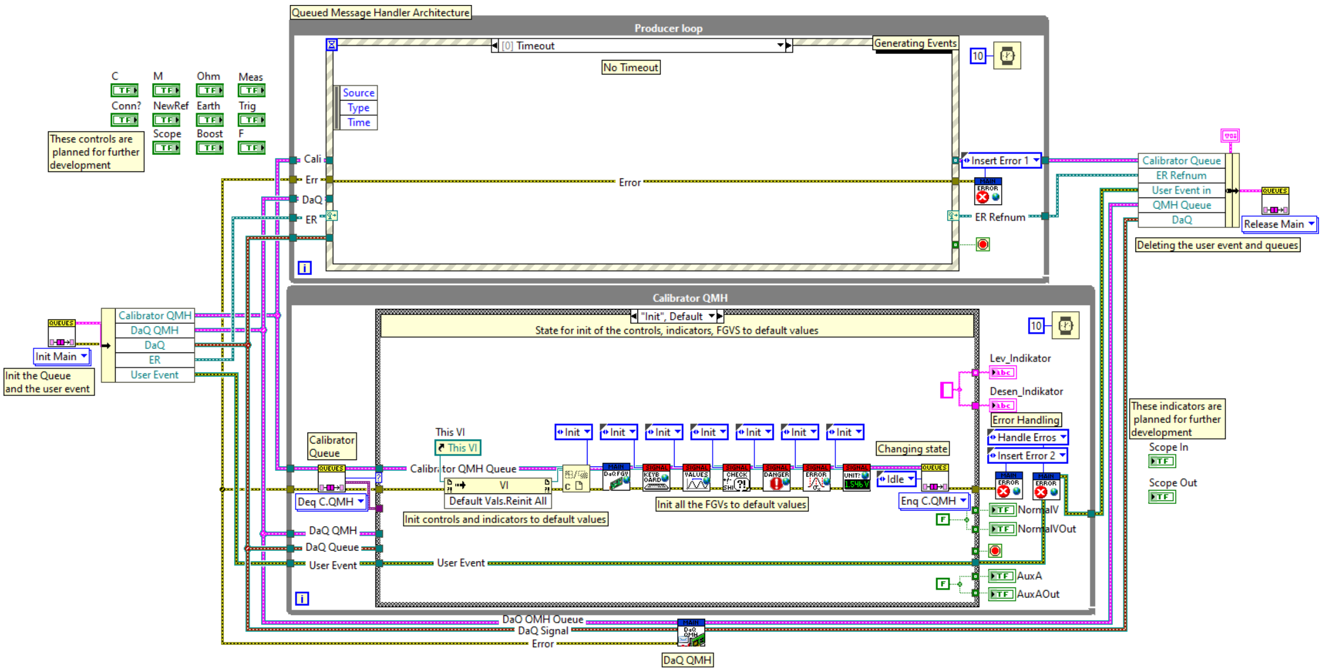

Fig. 3. Block diagram of the virtual calibrator. General view of the implemented programming architecture – queued message handler.

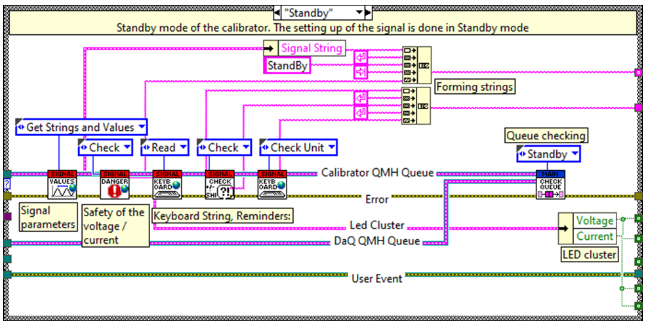

Fig. 4. Block diagram of the standby state in the calibrator loop

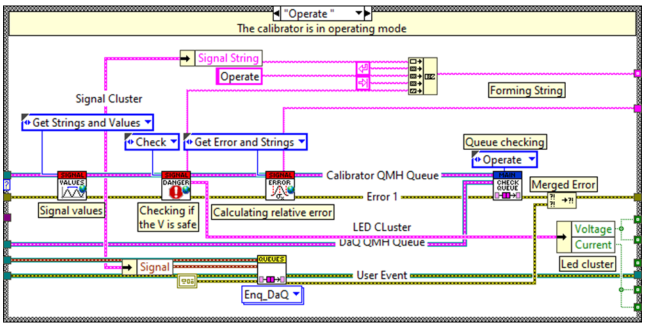

Fig. 5. Block diagram of the operate state in the calibrator loop

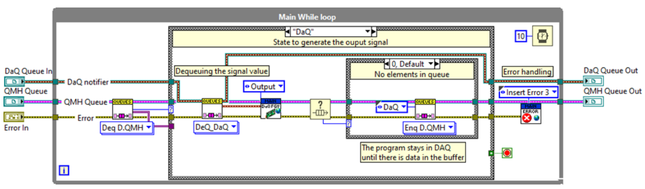

Fig. 6. Block diagram of the data acquisition loop

The third loop in Fig. 3 also consists of five different states: wait, message generation, start/stop acquisition, signal generation, and end. To perform the acquisition, a functional global variable is created which is called from one of the states. Regarding the signal generation, this variable is initiated when the measurement unit is selected because the type of task depends on whether the signal is voltage or current. The generated signal is a waveform data type containing the start time, time step, and array of double precision amplitude values. Two modes of signal acquisition are possible: finite and continuous. Considering applications related to real-time signal generation, the continuous acquisition mode is favourable. However, only some data acquisition cards support such acquisition mode. Therefore, considering the DAQ card used, the proposed virtual calibrator is realized by using the finite acquisition mode. It is also important to note that, when an external amplifier is used, the output signal from the DAQ card must be divided by the amplification coefficient.

B. Data acquisition card

The data acquisition card is used to reproduce the signals generated by the virtual instrument, thus having critical role regarding the metrological performances of the instrument. There are different types DAQ cards that can be used for realization of the proposed virtual calibrator. In general, the DAQ cards must contain an analog output channel for the signal generation. On the other hand, other technical specifications of the DAQ card are important considering the signal quality, such as: digital-to-analog (DA) converter resolution, sampling speed, acquisition mode, timing resolution, computer interface, etc. In order to have a wider impact, one of the mostly exploited low-cost DAQ card in the universities NI myDAQ was used within this paper. The most important technical parameters of NI myDAQ are summarized in table I.

TABLE I
IMPORTANT TECHNICAL PARAMETERS OF NIMYDAQ

Parameter	Quantity
DA converter resolution	16 bit
Sampling speed	200 kS/s
Analog output voltage	± 10 V
Output impedance	1 Ω
Maximal output current	2 mA
Timing resolution	2 ns

C. Power amplifier

The power amplifier is intended to amplify signals generated by a DAQ card with a "low voltage" output. The DA converter voltage of the DAQ card is usually standardized to a given voltage level, e.g. ±2.5 V, ±5 V or ±10 V. Such voltage levels are highly restrictive because they limit the calibration of instruments in a low measurement range. The aim of this section is to show one possibility to extend the output voltage range to the nominal power line voltage of 230V (or 110 V) prior connection with the instrument. The simplified block diagram of the power amplifier is given in Fig. 7.

The power amplifier is usually a digital system which reproduces the output signal by a DA converter. In such case, the DA converter must meet the metrological requirements regarding the desired output signal quality. Namely, it must have well-enough resolution (which is defined by the required output signal uncertainty), and support high-enough sampling frequency. Theoretically, the sampling frequency has to be at least twice higher than the frequency of the highest harmonic that needs to be generated. According the PQ standard EN50160 (takes up to 50th harmonic), the minimum sampling frequency is 5 kHz (for 50 Hz power grids). However, in practice the sampling frequency should be significantly higher to maintain the accuracy of the higher harmonics.

The generated signal with the DA converter is amplified by a PQ amplifier to the nominal power line voltage level of 230 V. To do so, several analog signal processing modules are used: low pass filter (restricts the input signal bandwidth and eliminate noise), preamplifier (amplifies the input signal to a given reference level and limits the input voltage level), power amplifier (amplifies the signal to nominal power line level and increase the load current capability). The detailed description of the power amplifier is given in [9], whereas its metrological performances are evaluated in [10].

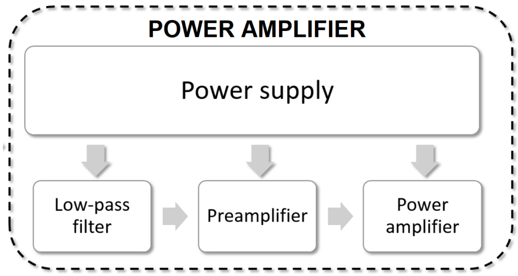

Fig. 7. Simplified block diagram of a power amplifier

The PQ amplifier was experimentally verified by using the PQ analyzer Fluke 435. The reference voltage waveforms, were generated by PC based virtual PQ signal generator [11]. The experimental system including PQ signal generator and reference instrument Fluke 435 is given in Fig. 8 and its practical implementation in Fig. 9.

The experiment was performed by using a data acquisition card NI PCIe 6343 containing analog output channel with maximal output voltage of ± 10 V. Signal with the first seven high-order odd harmonic was generated by using a virtual PQ generator with sampling frequency of 100 kS/s. The screenshots obtained from the FLUKE 435 front panel are given in Fig. 10 and Fig.11. The example given in Fig.10 represents signals with high-order harmonics, whereas the example given in Fig.11 shows occurrence of a burst transients.

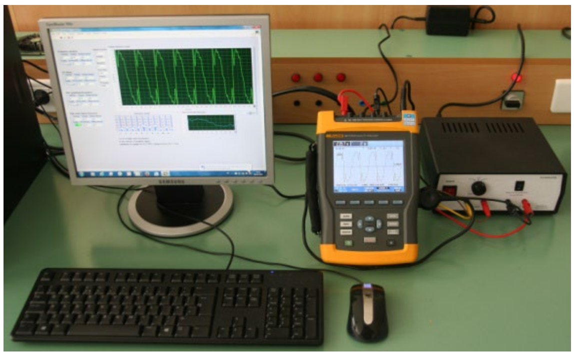

Fig. 8. Experimental system for verification of PC-based PQ signal generator

Fig. 9. Practical realization of the PQ amplifier

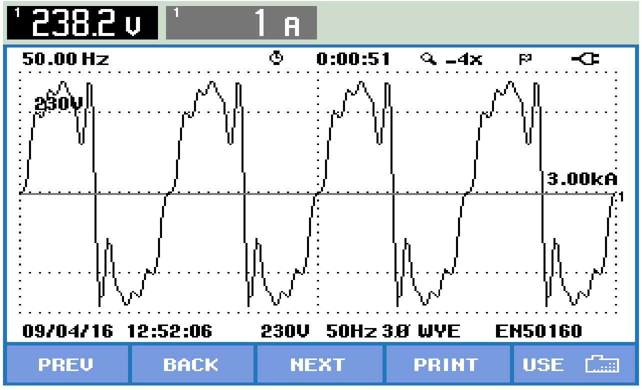

Fig. 10. Screenshot from the FLUKE 435 instrument. Signal with harmonics generated by PC and amplified with the PQ amplifier.

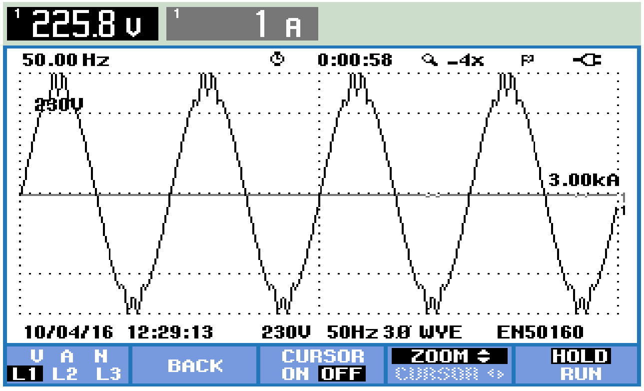

Fig. 11. Screenshot from the FLUKE 435 instrument. Burst transients generated by PC and amplified with the PQ amplifier.

III. Virtual Reference Standard Metrological Evaluation

The metrological performances of the virtual reference standard were evaluated by using a high precision instrument FLUKE 8846A with resolution of 6.5 digits. The measurement of the transfer function were performed for the direct current (DC) voltages in the range from 10-250V with a step of 10V, and for alternating current (AC) sinusoidal voltage with a root mean square (RMS) values from 10-250V with a frequency of 50Hz. The sampling frequency of the analog output channel was set to 1000 S/s. The amplifier input range of ± 5V was used resulting in amplification constant of 84.28.

The measured transfer characteristic of the virtual calibrator for DC voltage is given in Fig. 12, whereas the transfer characteristic for AC voltage is given in Fig. 13. Both transfer characteristics were approximated by using the least square methods resulting in a very low gain and offset component mainly originating from the power amplifier. Considering the results reported in Fig. 12 and Fig. 13 it can be seen that both transfer characteristics for DC and AC voltage are highly linear. In fact, when approximated by the least squares method the maximal non-linearity of the instrument is around 0.32 %. The overall uncertainty of the virtual calibrator can be additionally reduced if a higher output voltage range of the DAQ card is used, thus resulting in a lower amplification constant of the amplifier. Having in mind the DAQ card DA converter resolution of 16 bit (given in Table I), the theoretical output voltage resolution of the virtual calibrator in the measurement range of 250 V is 3.8 mV in a frequency range up to 3 kHz. The virtual calibrator can be also used in the current output mode, but having in mind the low output current capability of NI myDAQ, and external current amplifier have to be used. We could say that such performances of the virtual calibrator can be used for calibration and testing of low to medium accuracy instruments and can be successfully exploited in the laboratory practice in the higher education in the field of metrology.

The broader scope of such virtual reference standard realization is its integration into a remote virtual laboratory framework considered in the ongoing Erasmus+ project "A ubiquitous virtual laboratory framework – UbiLAB" under number 2020-1-MK01-KA226-HE-094548. It is envisaged that the virtual reference standard will coexist with a full palate of virtual laboratory instruments with a possibility to control remotely over the internet.

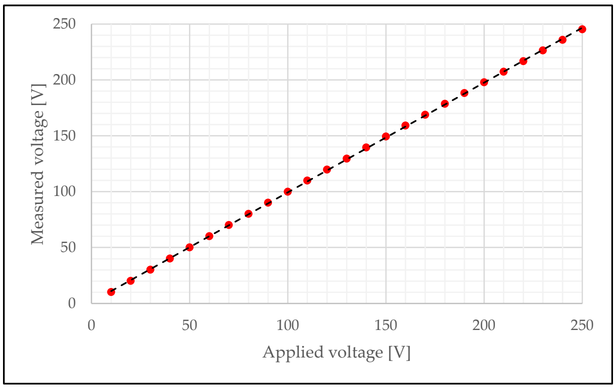

Fig. 12. Measured DC voltage transfer characteristics of the virtual calibrator in the range from 0 - 250 V

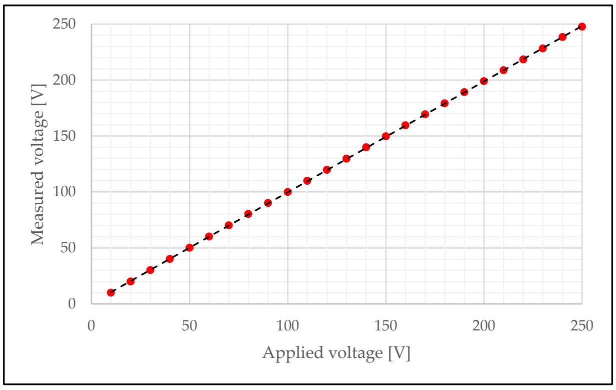

Fig. 13. Measured AC voltage transfer characteristics of the virtual calibrator in the range from 0 - 250 V

IV. Conclusion

The paper summarizes the design and implementation aspects of a virtual reference standard for electrical quantities aimed to be used in the higher education in the field of metrology. The paper is mainly focused on the implementation of the virtual instrument by using the queued message handler programming architecture. This programming architecture offers great modification flexibility which is crucial when used for education purposes. Besides the basic calibrator functionalities, the proposed realization offers possibility for data logging and automatic report generation. Moreover, the virtual instrument functional performances can be easily adjusted according the existing commercial instruments providing an additional value in the student's laboratory practice.

The metrological performances of the virtual calibrator were evaluated by using a high accuracy multimeter, power amplifier and a data acquisition card. The transfer characteristics of the virtual calibrator was measured in the measurement range of 250 V for DC and AC voltage with a frequency of 50 Hz. The experimental results suggested that the maximal nonlinearity error of the transfer characteristics are around 0.32%. The theoretical resolution of the virtual calibrator in this measurement range is 3.8 mV. We could say that such metrological performances can be considered satisfactory having in mind the simplicity of the solution. The virtual reference standard proposed herein is conceived as a part of ubiquitous remote laboratory framework which is to be published in future scientific publication.

Acknowledgement

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