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Original scientific paper

EXPERIMENTAL VALIDATION OF A VIRTUAL INSTRUMENT FOR POWER QUALITY MONITORING

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A b s t r a c t: This paper deals with experimental validation of a Virtual Instrument used for power quality monitoring. The Virtual Instrument is developed in the graphical programming language LabVIEW developed by National Instruments and uses specialized signal conditioning circuits and data acquisition card to perform the measurements. LabVIEW greatly enhances the power quality monitoring capabilities because of the short development time, easy creation of a user interface, high sampling rates. All of these factors makes virtual instrumentations more acceptable than classic power quality monitoring instruments. The main goal of this paper is to compare the developed virtual instrument with a power quality analyzer, Fluke 435. Also the uncertainty budgets for DC and AC voltages are evaluated for the virtual instrument. As a referent unit in the uncertainty budget evaluation the calibration Fluke 5500 A is used. From the obtained result the Virtual Instrument showed great capabilities for power quality monitoring

Key words: power quality; virtuai; LabVIEW; calibration

ЕКСПЕРИМЕНТАЛНА ВАЛИДАЦИЈА НА ВИРТУЕЛЕН ИНСТРУМЕНТ ЗА МОНИТОРИНГ НА КВАЛИТЕТОТ НА ЕЛЕКТРИЧНАТА ЕНЕРГИЈА

А п с т р а к т: Во овој труд се обработува експериментална валидација на виртуелен инструмент кој е наменет за мониторинг на квалитетот на електричната енергија. Виртуелниот инструмент е развиен во графичкиот програмски јазик LabVIEW кој е развиен од компанијата National Instruments и користи специјални кола за приспособување на сигналот и картица за аквизиција за негово мерење. LabVIEW во голема мера ги зголемува можностите за мониторинг на квалитетот на електричната енергија поради краткото време на развој на една апликација, лесното креирање на кориснички интерфејс, високите стапки на земање примероци. Сите овие фактори ја прават виртуелната инструментација поприфатлива од класичните инструменти за мерење квалитет на електричната енергија. Целта на овој труд е да се спореде виртуелен инструмент со комерцијален анализатор на квалитет на електрична енергија, Fluke 435. Исто така се одредуваат буџетите на мерна неодреденост на еднонасочни и наизменични напони. Како референтен инструмент при одредувањето на буџетот на мерна неодреденост се користи калибратор Fluke 5500A. Од добиените резултати виртуелниот инструмент покажува добри карактеристики за мониторинг на квалитетот на електричната енергија.

Клучни зборови: квалитет на електрична енергија; виртуелен инструмент; LabVIEW; калибрација

1. INTRODUCTION

The interest in Power Quality (PQ) increased at the end of 20th century. The need for PQ monitoring comes from the increase usage of renewable energy sources, industrial development of the world and increased usage of power electronics in the power grids. Bad PQ can lead to damage to equipment and economic losses. There are couple of definitions for the concept of PQ. Some refer it as current quality, others as voltage quality. In this paper voltage quality will be used as a definition for PQ [1, 2].

There are several standards that define PQ and the means of monitoring power quality from which most used are IEC-61000-4-30 and IEEE Std 1599-2019. Besides of the PQ definition, these standards also define the events that can occur and the mathematical methods that are used in the monitoring. There are several types of instruments that can be used for PQ monitoring that are referred in the upper mentioned standards from basic multimeters, oscilloscopes, event loggers and the most used PQ analyzers. PQ analyzers have been programmed according to the mathematical methods mentioned in the standards and most of them are programmed according to the IEC-61000-4-30 standard. These analysers have the option to calculate voltage root mean square (RMS) with various aggregation times, total harmonic distortion (THD), event classifycation and logging, flicker meter, current measurement, etc. Although this instruments have excellent performances they are also quite expensive [3–[5].

Inspired by the previous fact a Virtual Instrument for power quality monitoring is developed. Virtual instrumentation (VI) is the newest generation of instrumentation. This instrument uses the computing power of personal computers for data visualization and processing. They consist of software part that is installed on the personal computer and data acquisition (DAQ) device that is used to acquire the signals. VI is usually developed in a graphical programming environment from which the most popular is LabVIEW. LabVIEW allow easy development of user interface, fast development of complex algorithms, and easy connectivity with various of communication protocols and hardware. The biggest advantage of LabVIEW is the reusability and scalability which makes VI developed in LabVIEW much more acceptable option from a financial point of view. In the recent years LabVIEW has been used to create PQ instruments and even performing real on grid measurements [6–10].

The main goal of this paper is to test the metrological capabilities of this kind of instrument and compare it with traditional power quality instrument. The first part of the paper contains short explanation of the Virtual Instrument for power quality monitoring. The focus in the paper will be attributed to experimental validation. Firstly, the VI uncertainty budget is evaluated, with the help of FLUKE 5500A calibrator as a referent unit. Afterwards the VI is compared to a commercial PQ analyzer Fluke 435. Both instruments measure voltage disturbances generated by a Virtual PQ disturbance generator.

2. VIRTUAL INSTRUMENT FOR POWER QUALITY MONITORING

The user interface of the VI contains two parts:

- Configuration: in this part of the VI the user configures the characteristics of the power grid and picks the type of measurement.
- Instrument: the user can pick any of the configured instruments.

The user interface is shown at Figure 1. The user can select of the two modes of operation:

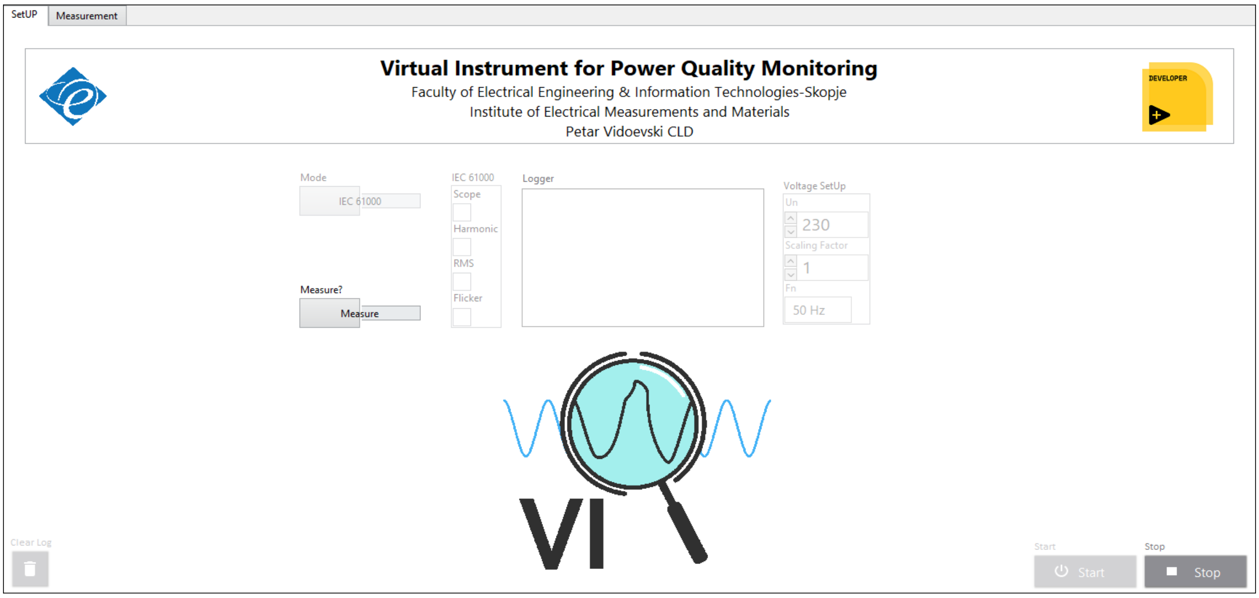


Fig. 1. User interface of the Virtual Instrument for power quality monitoring

- IEC 61000: this mode of operation performs measurement according to the standard IEC 61000-4-30. The user can pick between RMS analysis, harmonic analysis and oscilloscopic view of the signal.
- Wavelet: this mode performs wavelet transform and machine learning classification algorithm.

The programme also has calibration mode of operation when the user can test the instrument in various sampling rates. The VI uses NI my-RIO 1900 as a DAQ device. It has Real-Time processor and Front Programmable Gate Array (FPGA) chip [11]. Because of its high sample rates, real-time processing and easy connectivity with LabVIEW it is a potential candidate for a good PQ instrument.

2.1. *RMS analysis*

This part of the virtual instrument performs RMS analysis according to aggregation periods given in IEC 61000-4-30. The fundamental aggregation period is 200 ms. It comes from 10/12 periods of 50/60 Hz sine voltage. The RMS for this period can be calculated according the equation (1) [1, 3].

$$U_{rm_{200}ms} = \sqrt{\frac{1}{200}\int_{200\ ms} U^2(t)dt} \qquad (1)$$

The next aggregation period is 3 s and it is formed from fifteen two hundred millisecond RMS values. The 3s RMS is calculated with equation (2).

$$U_{rm_{200}ms} = \sqrt{\frac{1}{200}\int_{200\ ms} U^2(t)dt} \qquad (2)$$

Next is the 10 min periods and it is obtained from two hundred three second values. The 10 min RMS is calculated according to equation (3).

$$U_{\mathrm{rms\_10\ min}} = \sqrt{\frac{1}{200}\sum_{i=1}^{200} U^2_{i,\ \mathrm{rms\_3\ s}}} \qquad (3)$$

The last period is 2 h and it is obtained from tvelve ten-minute values. The 2 h RMS is calculated according to equation (4).

$$U_{\mathrm{rms\_2\ h}} = \sqrt{\frac{1}{12}\sum_{i=1}^{12} U^2_{i,\ \mathrm{rms\_10\ min}}} \qquad (4)$$

In some papers also 1 min aggregation period is proposed.

Also part of the RMS analysis the classification of voltage dip, voltage interruption and voltage swell via the RMS voltage of half period, $U_{\mathrm{RMS}(1/2)}$ is done. The algorithm is visualized on Fig. **2** [2][3]. The algorithm compares the measured $U_{\mathrm{RMS}(1/2)}$ with the nominal voltage that the user has given in the setup of the VI. When the $U_{\mathrm{RMS}(1/2)}$ crosses the threshold of $0.9U_n$ voltage dip event starts and it ends when the $U_{\mathrm{RMS}(1/2)}$ crosses above the $0.9U_{\mathrm{n}}$ threshold. On the other hand, while in voltage dip event if $U_{\mathrm{RMS}(1/2)}$ crosses the $0.05U_{\mathrm{n}}$ threshold voltage interruption events starts and it ends when the

$U_{RMS(1/2)}$ crosses above the $0.9U_n$ threshold. Also when $U_{RMS(1/2)}$ crosses the $1.1U_n$ threshold voltage swell event starts and it ends when $U_{RMS(1/2)}$ goes bellow that threshold.

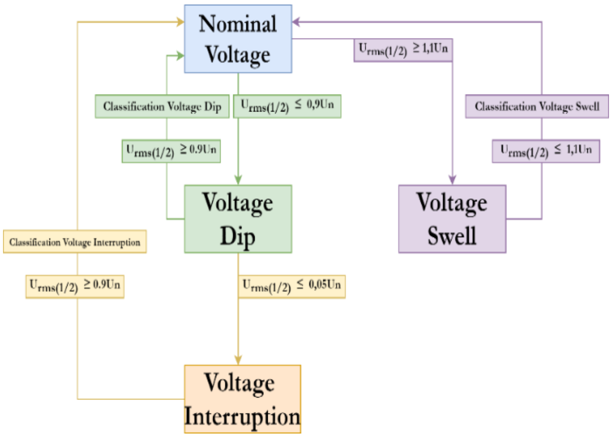


Fig. 2. Classification algorithm via $U_{RMS(1/2)}$

The $U_{RMS(1/2)}$ and the $U_{RMS(200\text{ ms})}$ are calculated after the first positive zero crossing is found 0. The sampling rates for 50/60 Hz system are given in Table 1.

2.2. *Harmonic analysys*

The harmonic analysis VI calculates the THD and harmonics components to the 50th harmonic. The THD is calculated according the equation (5), where U_1 is the fundamental component and U_i is the i^{th} component. The calculations are done in a 200 ms window after finding of the first positive zero crossing.

$$THD_U = \frac{\sqrt{\sum_{i=2}^{\infty} U_i^2}}{U_i} \tag{5}$$

Both the harmonic and RMS analysis are saving the measurements in a Comma Separated Values (.csv) files and they are compared with the data logged by Fluke 435.

Table 1

Sampling characteristics of the VI

Frequency	Number of samples of the measurement	Half period number of samples	Buffer size	Total number of samples	Number of samples after finding the first positive zero crossing	Sampling frequency (kHz)
50 Hz	4000	1000	6	24000	20000	100
60 Hz	3334	833	7	23333	20000	100
Wavelet analysis	22000	/	1	22000	20000	100

3. UNCERTAINTY BUDGET EVALUATION

The uncertainty budget is evaluated according to the standard "Guide to the Expression of Uncertainty in Measurements (GUM)" 0, 0. There are two types of uncertainties:

- Type A: This uncertainty is obtained via statistical analysis from a given number of measurements.
- Type B: this uncertainty is obtained from methods different than a statistical analysis like results from previous calibrations, experience of a given process, datasheets.

The type B uncertainties in this evaluation are obtained from the datasheets of the calibrator Fluke 5500A and NI myRIO-1900.

Fluke 5500A datasheet states normal distribution, with probability distribution of 99% what corresponds to coverage factor of k = 2.58 0.

The accuracy and stability of the calibrator DC voltages for the range of 0 to 3.3 V are given in equations (6) and (7), respectively, and for the voltage range of 0 – 33,3 V are given in equations (8) and (9). The accuracy of the calibrator sine voltage characteristics are obtained from the 45 Hz to 100 kHz frequency range. The accuracy of the calibrator for sine voltages are given in equations (10) and (11).

$$\Delta U = 0{,}005\ \%\ U_c + 5\ \mu\text{V, resolution } 1\ \mu\text{V} \tag{6}$$

$$\Delta U_s = 4\text{ ppm }\ U_c + 3\ \mu\text{V, resolution } 1\ \mu\text{V} \tag{7}$$

$$\Delta U = 0{,}005\ \%\ U_c + 50\ \mu\text{V, , resolution } 10\ \mu\text{V} \tag{8}$$

$$\Delta U_s = 4\text{ ppm }\ U_c + 3\ \mu\text{V, , resolution } 10\ \mu\text{V} \tag{9}$$

$$\Delta U = 0{,}03\ \%\ U_c + 50\ \mu\text{V, resolution } 10\ \mu\text{V} \tag{10}$$

$$\Delta U = 0{,}04\ \%\ U_c + 600\ \mu\text{V, resolution } 10\ \mu\text{V} \tag{11}$$

In the previous equations ΔU is the accuracy of the calibrator, ΔU_s is the error because of stability, and U_c is the output voltage of the calibrator.

The uncertainty contributions from NI myRIO-1900 are the accuracy of NI myRIO-1900 and the resolution. In the NI myRIO-1900 datasheet the distribution was not stated, so rectangular distribution is assumed.

The chosen measurement points are chosen from the beginning, middle and the end of the measurement range of the NI myRIO-1900 analog channel that is used. The VI is tested for three different frequencies: 50 Hz, 1 kHz and 10 kHz. All of the measurements are done with fixed 100 kHz sampling frequency. The sine voltages were measure for 10 periods, after detecting the first positive zero crossing.

The DC voltage uncertainty contributions are shown in Table 2. The biggest contributor of the uncertainty is the NI myRIO-1900, whereas the other components are almost negligible. This means that the performance of the VI can be increased with using better data acquisition device, or increasing the sampling rate.

The sine voltage measurement results are shown graphically in Figure 3 and Figure 4. In Figure 3 the average value of the measurements for all three frequencies and measurement points are shown, whereas Figure 4 shows the expanded uncertainty.

In the sine wave measurement also the biggest contributor of the uncertainty is the NI myRIO-1900. Also the 1 kHz and especially the 10 kHz measurements need to be taken with a little reserve because waveform distortion occurs when reading the higher frequencies. This effect occurs because of the fixed sampling rate and the fix number of periods. As can be seen from the results the uncertainty is the highest at the 10 kHz sine voltage. Better way of conducting this multi-frequency validation is to make the time (e.g. 200 ms) fixed, and to calculate the needed periods from it, like it is done by the 10/12 period 50/60 Hz rule that is stated in IEC 61000-4-30.4.

Table 2

DC voltage uncertainty contributions

Contributions	Measurement uncertainty						
	–10 V	–9 V	–5 V	–1 V	1 V	5 V	8 V
Repetition	0.001528	0.000876	0.000676	0.000399	0.000267	0.002844	0.008771
Accuracy of myRIO	0.115467	0.115467	0.115467	0.115467	0.115467	0.115467	0.115467
Resolution of myRIO	0.00141	0.00141	0.00141	0.00141	0.00141	0.00141	0.00141
Accuracy of Fluke 5500 A	0.000213	0.000194	0.000116	0.000021	0.000021	0.000116	0.000174
Resolution of Fluke 5500 A	0.000002	0.000002	0.000002	0.000001	0.000001	0.000002	0.000002
Stability of Fluke 5500 A	0.000027	0.000026	0.000019	0.000003	0.000003	0.000019	0.000024
Combined measurement uncertainty u_c	0.11548	0.11547	0.11547	0.11547	0.11547	0.11551	0.1158
Effective degrees of freedom (V_{eff})	∞	∞	∞	∞	∞	∞	∞
Coverage Factor K	2	2	2	2	2	2	2
Expanded measurement uncertainty U_m, K = 2	0.23097	0.23095	0.23095	0.23095	0.23095	0.23102	0.23161
Expanded measurement uncertainty U_m, K = *f*(veff)	0,23097	0,23095	0,23095	0,23095	0.23095	0.23102	0.23161
	Confidence intervals						
	–10 V	–9 V	–5 V	–1 V	1 V	5 V	8 V
	K = 2						
Upper limit	–10.2022	–9.1914	–5.1989	–1.2255	0.7671	4.777	7.7805
Average	–9.9712	–8.9604	–4.9680	–0.9946	0.9981	5.0080	8.0122
Lower limit	–9.7402	–8.7294	–4.7370	–0.7636	1.2290	5.2390	8.2438
	K = *f* (V_{eff})						

Upper limit	–10.2022	–9.1914	–5.1989	–1.2255	0.7671	4.7770	7.7805
Average	–9.9712	–8.9604	–4.9680	–0.9946	0.9981	5.0080	8.0122
Lower limit	–9.7402	–8.7294	–4.7370	–0.7636	1.2290	5.2390	8.2438

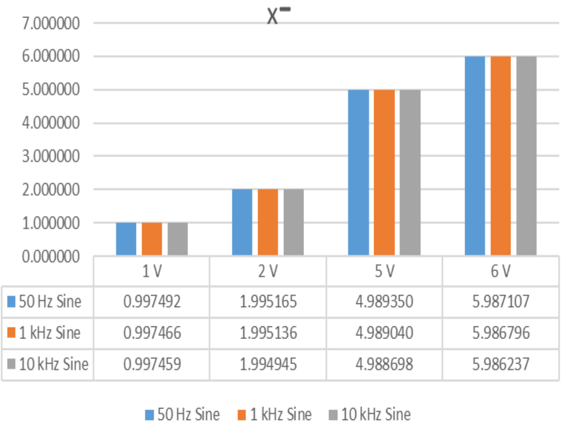


Fig. 3. Average values for the sine voltage measurements

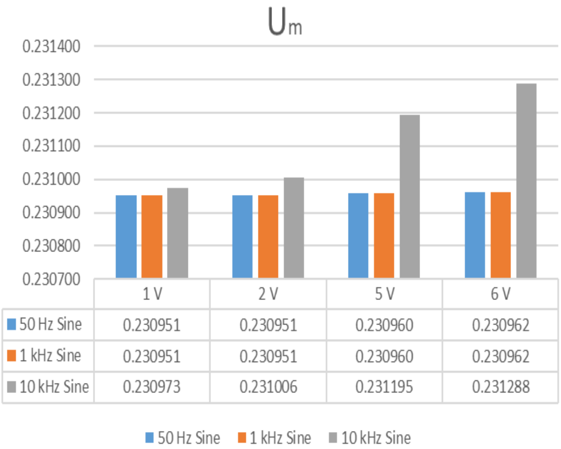


Fig. 4. Expanded uncertainty for the sine voltage measurements

4. EXPERIMENTAL VALIDATION AND DISCUSSION

The VI is compared with Fluke 435 power analyzer [17]. The both instrument measure PQ disturbances generated by a Virtual PQ Disturbance Generator, in one hour duration time [18]. The values compared are:

- Half period RMS
- 200 ms RMS
- THD distortion
- Event logging

The process of the experimental testing is shown on Figure 5.

NI USB-6218 is used for generating the voltage disturbances. The signal that is interfaced to the Fluke 435 is initially amplified via voltage disturbance amplifier in order to achieve the power line voltage levels [19]. In the virtual instrument, the scaling is done programmatically. The result of the voltage RMS (Figure 6) and THD (Figure 7) are presented via a histogram.

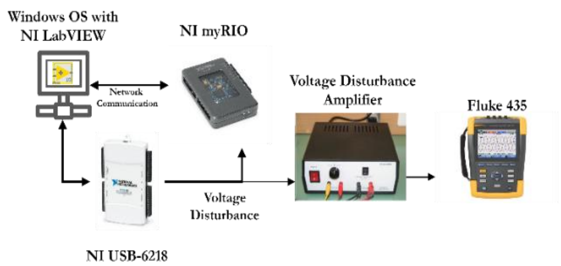
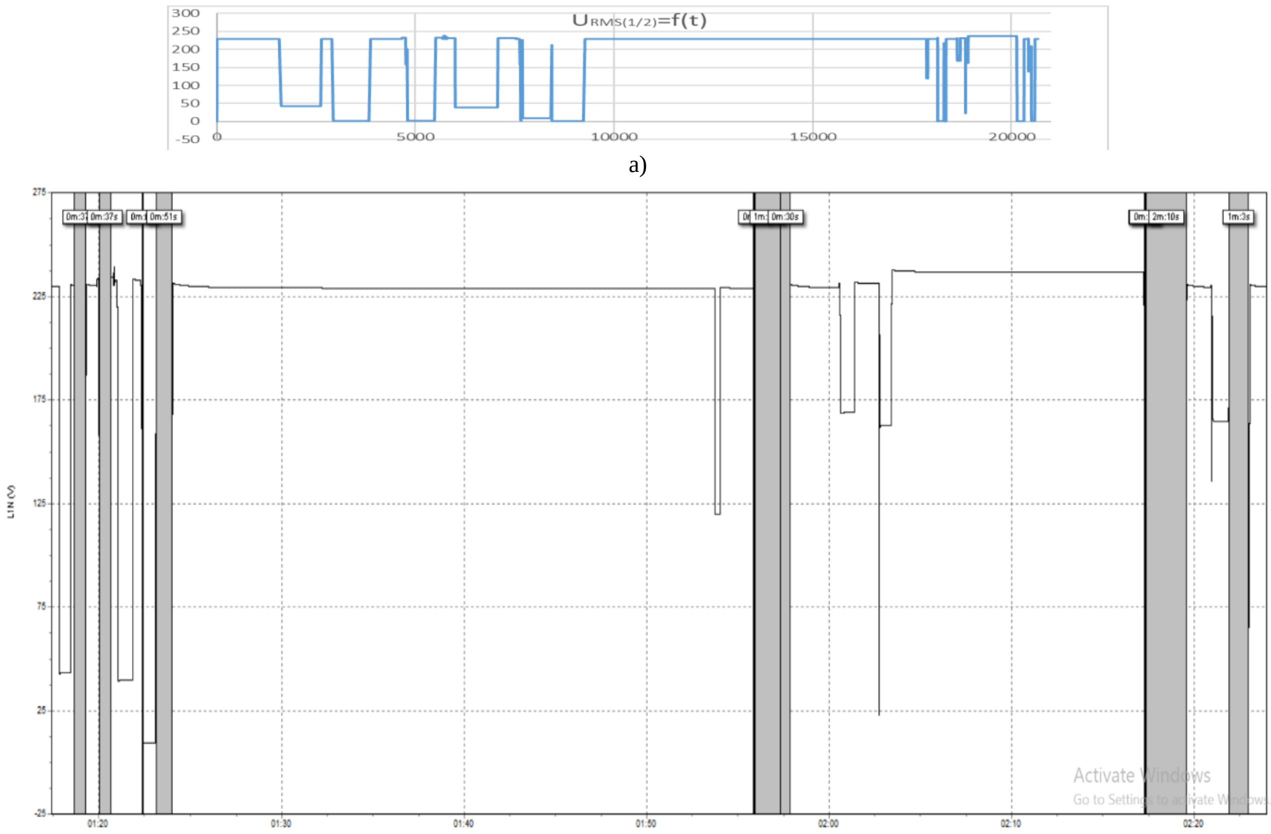


Fig.5. Block diagram of the experimental testing



a)

b)

Fig. 6. Histogram representation of $U_{RMS(1/2)}$:
a) Measurements done by the Virtual Instrument for power quality monitoring,
b) Measurements done by FLUKE 435 power quality analyzer

From the obtained results can be seen that the histogram obtained by the VI is very close to that acquired by Fluke 435. There are couple of errors that can affect the result. One is the approximation of the multiplication factor that scales the measurement in the VI, to match the amplification coefficient of the PQ amplifier. Also this testing helped to detect a problem of the instrument when calculating the longer aggregation periods that is the delay that is produced because of the samples that are lost when performing the detection of the first positive zero crossing. This delay is negligible for the short aggregation periods and the $U_{\mathrm{RMS}(1/2)}$. A log file of the classified events by Fluke 435 is not provided in by the instrument. The detected events are shown on the histogram (Fig. 6b). There is a difference between the classification of Fluke 435 and the VI. Namely the voltage interruption is classified as two events, first a voltage dip and then a voltage interruption. Therefore the classification results can't be compared in detail, but they can approximately be compared with the histogram given in Figure 6b.

The THD_u results are also represented with a histogram shown on Figure 7. The VI has also shown great results, obtaining very similar results to the Fluke 435 measurements. There is one peak value that Fluke 435 registered which is bigger than the measurements done by the VI. Having in mind that this is a single occurrence it can be assumed that was probably provoked by an interference.

An example of a voltage interruption during the experimental validation is shown in Figure 8, the classification results are also shown in Table 3.

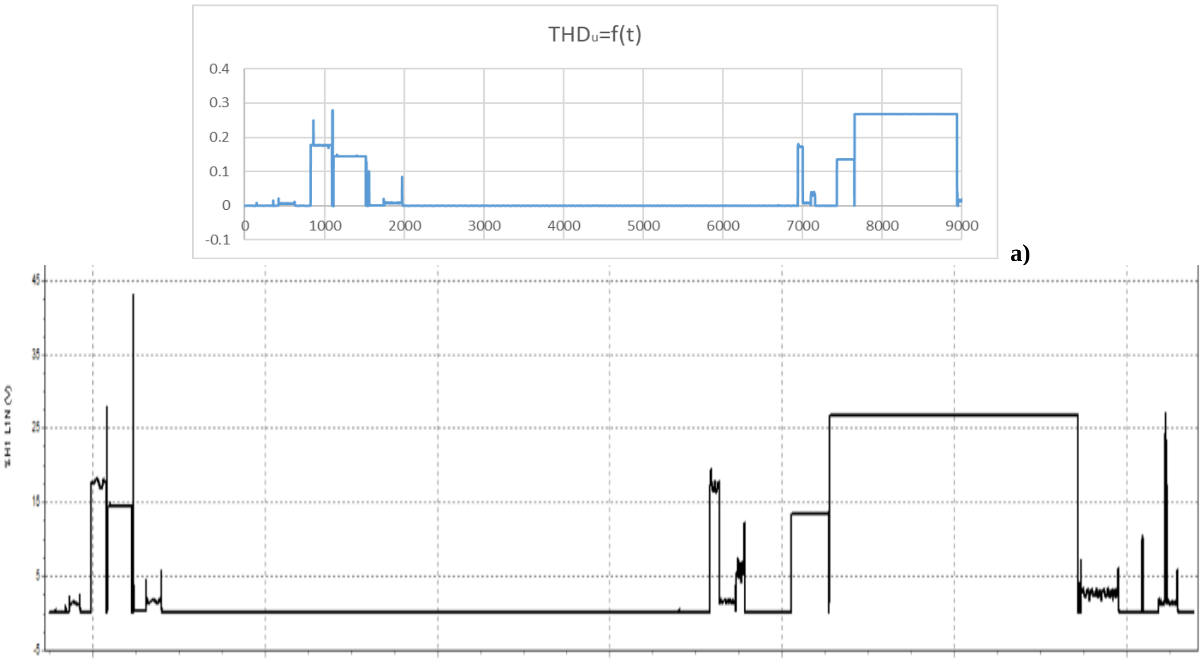


Fig. 7. Histogram representation of THD_u:
a) Measurements done by the Virtual Instrument for power quality monitoring
b) Measurements done by FLUKE 435 power quality analyzer

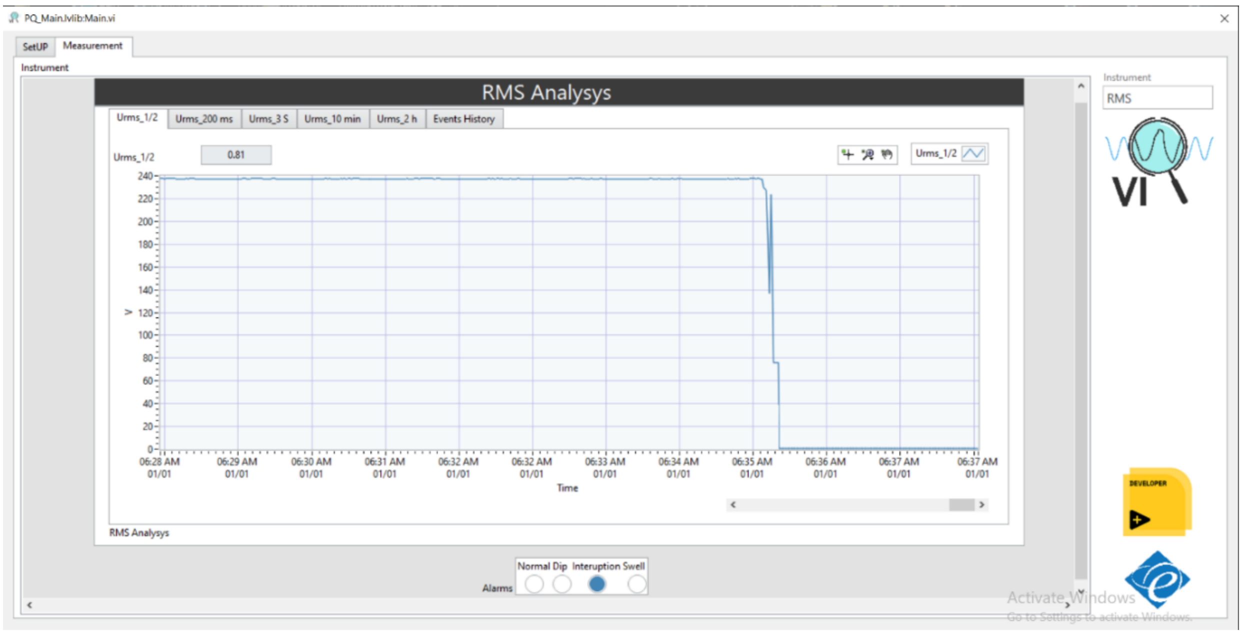


Fig. 8. Example of a voltage interruption during the experimental validation

Table 3

Classification results

Event	Start time	End time	Duration (s)	Value (%)
Dip	7/14/2021 11:33	7/14/2021 11:34	37.400017	18,57
Interruption	7/14/2021 11:34	7/14/2021 11:35	39.923297	0,74

Interruption	7/14/2021 11:35	7/14/2021 11:36	41.250752	0,81
Dip	7/14/2021 11:36	7/14/2021 11:37	50.141984	16,88
Interruption	7/14/2021 11:38	7/14/2021 11:38	2.055502	0,83
Dip	7/14/2021 11:38	7/14/2021 11:38	0.635308	63,1
Dip	7/14/2021 11:38	7/14/2021 11:38	0.928517	46,55
Interruption	7/14/2021 11:38	7/14/2021 11:38	42.427602	3,97
Interruption	7/14/2021 11:38	7/14/2021 11:39	54.500334	0,59
Dip	7/14/2021 12:09	7/14/2021 12:09	17.732605	52,08
Interruption	7/14/2021 12:11	7/14/2021 12:11	2.706769	0,15
Interruption	7/14/2021 12:11	7/14/2021 12:13	84.574381	0,6
Interruption	7/14/2021 12:13	7/14/2021 12:13	30.046659	0,15
Dip	7/14/2021 12:16	7/14/2021 12:17	48.180229	73,3
Dip	7/14/2021 12:18	7/14/2021 12:19	42.200212	9,9
Dip	7/14/2021 12:33	7/14/2021 12:33	1.428201	59,44
Interruption	7/14/2021 12:33	7/14/2021 12:35	137.410435	0,35
Dip	7/14/2021 12:36	7/14/2021 12:36	1.530910	60,79
Interruption	7/14/2021 12:36	7/14/2021 12:38	123.101709	0,7

5. CONCLUSION

The paper elaborates the implementation and validation of a virtual instrument used in power quality monitoring. The validation process was performed in two parts. Initially, the uncertainty budget was evaluated and then the VI was experimentally validated with a commercial PQ analyzer, Fluke 435. It has been shown that the developed virtual instruments produce very good measurement results compared to the commercial instrument Fluke 435. The virtual instruments successfully detected the power quality disturbances (voltage deeps and interruptions), as well as provided a good-matching envelope of the total harmonic distortion measurements. On the other hand, the validation procedure exposed possible problems of the instruments like the delay in the longer aggregation periods because of the detection of the first zero crossing, that should be corrected in future versions of the VI implementation.

The second part of the paper deals with the uncertainty budget evaluation. The detailed budged evaluation showed that NI myRIO-1900 appeared as the biggest budget uncertainty contributor. It is however to be expected that using some other versions of RIO system, like cRIO, will decrease the uncertainty of the measurements.

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