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Calibration of a Virtual Instrument for Power Quality Monitoring

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Abstract. The paper describes a virtual instrument for power quality monitoring based on NI LabVIEW™ platform and simultaneous measurements of electrical voltages and currents. The virtual power quality analyzer is realized by using National Instruments 9225 and 9227 modules for voltage and current measurements, respectively, NI cDAQ 9174, 4 slot USB chassis and a PC. The created virtual instrument measures power quality characteristics: power frequency, voltage variations, magnitude of rapid voltage changes, flicker severity, voltage unbalance, total harmonic distortion, as well as the elements of voltage dips, short interruptions, and long interruptions defined in the standard EN 50160 for voltage characteristics of supplied electricity. The measurement is according to the general guide on harmonics and interharmonics measurements IEC 61000-4-7. The calibration and verification of the power quality analyzer is a complex task and it is performed by using the laboratory calibrator FLUKE 5500A. The results of calibration and verification of the developed virtual instrument, as well as the results of power quality measurements near different lightning technologies are presented.

Key words

Power quality, power quality analyzer, virtual instrument, calibration, LabVIEW™.

1. Introduction

The continual implementation of new renewable electricity sources like photovoltaic (PV) panels, wind turbines and the growth of nonlinear industrial and domestic loads cause voltage distortion, voltage dips and other different types of disturbances in the electricity network. The dealing with this growing problem implies study of certain sources of disturbances of the power quality as well as research of their interactions with the power system, [1]. The characteristics of the electrical power supply together with the limits specifications, which define the power quality supply, are defined in the international standard EN 50160, [2]. This implies the need of constant monitoring of the defined characteristics by proper instruments in compliance to the international guide IEC 61000-4-7, [3]. On the other hand the usage of the personal computers (PC) in the measurement technique and the availability of I/O modules and data acquisition cards (DAQ) enable cheap and fast creation of virtual instruments for physical measurements. So, for the study and analysis of the problems connected to the power quality, a virtual power quality analyzer based on National Instruments™ (NI) input modules, NI USB chassis, PC and LabVIEW™ platform is developed.

2. Description of the hardware

Two modules for the Analog input are used:

1) NI 9225, 3-channel 300 V rms Analog input module with 50 kS/s per channel simultaneous inputs for phase voltage measurement and built-in antialias filters.
2) NI 9227, 4-channel current input, 5 A rms measurement, 50 kS/s per channel simultaneous inputs and built –in antialias filters.

Other equipment used:

3) NI cDAQ-9174, compact DAQ, 4 slot chassis with USB connection. The chassis runs the Analog input modules simultaneously. The chassis has four general purpose 32 bit counter/timers built-in.

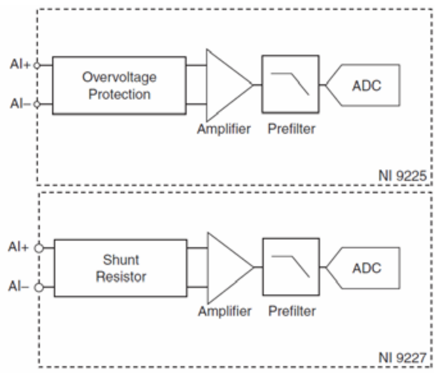

Fig. 1. Input circuits for one channel of NI 9225 and NI 9227

The input circuit for one channel of NI 9225 and NI 9227 is shown in Figure 1. The Delta-Sigma ADCs are with 24 bits. The internal master time-base is f_M=12,8 MHz. The accuracy is ±0,23 % of the read value, ±0,05 % of the range (for temperature range from -40 °C to 70 °C). The wiring diagram of the power quality analyzer for direct measurement of the phase voltages and currents is shown in Figure 2.

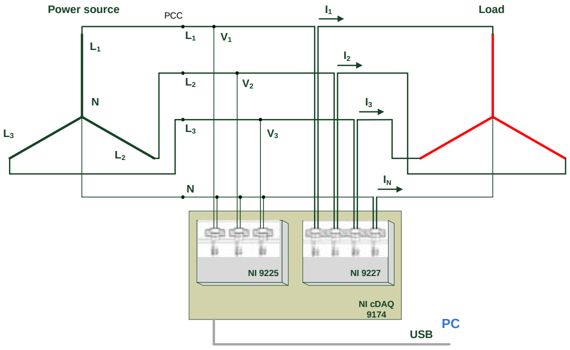

Fig. 2. Wiring diagram of the power quality analyzer

3. LabVIEW created virtual power quality analyzer

The LabVIEW™ graphical programming language was used for creation of the virtual instrument for measurement of the power quality characteristics. The graphical source code of the virtual instrument is shown in Figure 3.

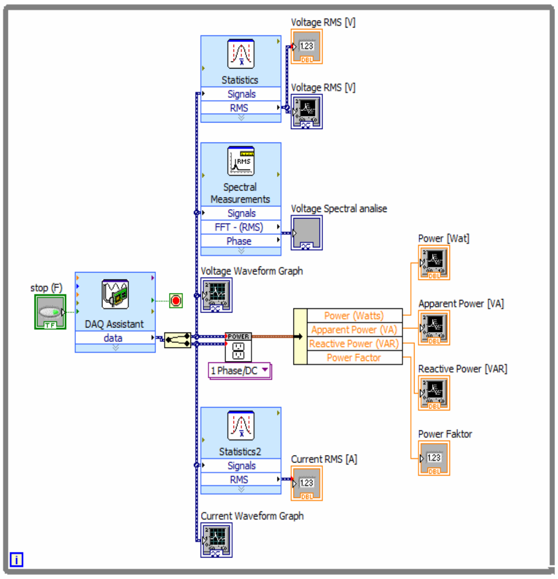

Fig. 3. Simplified block diagram of the software of the PQ virtual instrument

The virtual instrument beside the measurement of the phase voltages, phase and neutral current, also contains software modules running in parallel:

- EN 50160 voltage monitor
- FFT analyzer
- Vector analyzer
- Flicker analyzer
- Power monitor.

Relating to the measurement of the powers in non-sinusoidal conditions, there were lots of discussions and different definitions of reactive power in the past.

It has begun with Budeanu [5] who introduced reactive power Q, a quantity named distortion power D and finishing with the IEEE working group on harmonics [6]. The IEEE working group on “nonsinusoidal situations” has suggested”practical definitions for powers”, [6]. The main difference between this definition and other definitions is that it separates the fundamental quantities P_1 and Q_1 from the rest of the apparent power components. All the different definitions were focused on particular aspects of power quality problematics, measurement for energy billing, evaluation of the quality, detection sources of distortion and dynamic compensation. The IEEE working group put the focus rather on revenue metering than on compensation. The new definitions were developed to give guidance with respect to the quantities that should be measured for revenue purposes, engineering economic decisions, and determination of major harmonic polluters.

It may be concluded that there is not yet available a generalized power theory which can provide a simultaneous common base for energy billing, evaluation of electric energy quality, detection of the major sources of waveform distortion, theoretical calculations for the design of mitigation equipment such as active filters or dynamic compensators, [7].

The virtual instrument using a computer enables accurate, and versatile metering of electrical quantities defined by means of advanced mathematical models. Depending on the purpose of the measurement, different definitions of powers and power quality parameters can be easily implemented.

Measurements presented in the paper are according to IEEE Std 1459/2010, IEEE Standard Definitions for the Measurement of Electric Power Quantities under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions [7]. The power characteristics are defined as follows.

The *instantaneous power p* is given by

$$p = v \cdot i \tag{1}$$

The *active power P*, which is also called *real power*, is the average value of the instantaneous power during the measurement time interval τ to $\tau + kT$, as follows:

$$P = \frac{1}{kT}\int_{\tau}^{\tau+kT} p\,dt \tag{2}$$

$$P = \frac{1}{kT}\int_{\tau}^{\tau+kT} (v \cdot i)\,dt \tag{3}$$

where, $T = 1/f$ is the cycle time in [s], k is a positive integer number, τ is the moment when the measurement starts.

The *apparent power S* is the product of the root-mean-square (rms) voltage and the rms current.

$$S = V \cdot I \tag{4}$$

$$S = \sqrt{P^2 + Q^2} \tag{5}$$

The *power factor* is defined as:

$$PF = \frac{P}{S} \tag{6}$$

Single-Phase nonsinusoidal-For steady-state conditions, a nonsinusoidal periodical instantaneous voltage or current comprises two distinct components: the power system frequency components v_1 and i_1 and the remaining term v_H and i_H respectively.

$$v = v_1 + v_H \tag{7}$$

and

$$i = i_1 + i_H \tag{8}$$

where

$$v_1 = \sqrt{2} V_1 \sin(\omega t - \alpha_1) \tag{9}$$

$$i_1 = \sqrt{2} I_1 \sin(\omega t - \beta_1) \tag{10}$$

$$v_H = V_0 + \sqrt{2} \sum_{h>1} V_h \sin(h\omega t - \alpha_h) \tag{11}$$

$$i_H = I_0 + \sqrt{2} \sum_{h>1} I_h \sin(h\omega t - \beta_h) \tag{12}$$

The corresponding rms values squared are as follows:

$$V = \sqrt{\frac{1}{kT} \int_{\tau}^{\tau+kT} v^2 dt} \quad \text{and} \quad V^2 = V_1^2 + V_H^2 \tag{13}$$

$$I = \sqrt{\frac{1}{kT} \int_{\tau}^{\tau+kT} i^2 dt} \quad \text{and} \quad I^2 = I_1^2 + I_H^2 \tag{14}$$

where

$$V_H^2 = V_0^2 + \sum_{h>1} V_h^2 = V^2 - V_1^2 \tag{15}$$

$$I_H^2 = I_0^2 + \sum_{h>1} I_h^2 = I^2 - I_1^2 \tag{16}$$

are the squares of the rms values of v_H and i_H, respectively.

Total harmonic distortion (THD)-The overall deviation of a distorted wave from its fundamental can be estimated with the help of the total harmonic distortion. The total harmonic distortion of the voltage is as follows:

$$THD_v = \frac{V_H}{V_1} = \sqrt{\left(\frac{V}{V_1}\right)^2 - 1} \tag{17}$$

The total harmonic distortion of the current is as follows:

$$THD_i = \frac{I_H}{I_1} = \sqrt{\left(\frac{I}{I_1}\right)^2 - 1} \tag{18}$$

In this case the active power is:

$$P = P_1 + P_H \tag{19}$$

The *fundamental active power* is:

$$P_1 = \frac{1}{kT} \int_{\tau}^{\tau+kT} v_1 i_1 dt = V_1 I_1 \cos\theta_1 \tag{20}$$

The *harmonic active power* (nonfundamental active power) is:

$$P_H = V_0 I_0 + \sum_{h>1} V_h I_h \cos\theta_h = P - P_1 \tag{21}$$

The *fundamental reactive power* is:

$$Q_1 = \frac{\omega}{kT} \int_{\tau}^{\tau+kT} i_1 \left[\int v_1 dt\right] dt \tag{22}$$

$$Q_1 = V_1 I_1 \sin\theta_1 \tag{23}$$

The *fundamental apparent power* S_1 and its components P_1 and Q_1 are the actual quantities that help the definition of the rate of flow of the electromagnetic field energy associated with the fundamental voltage and current. This is a product of high interest for both the utility and the end-user.

$$S_1 = V_1 \cdot I_1 \tag{24}$$

$$S_1^2 = P_1^2 + Q_1^2 \tag{25}$$

Nonfundamental apparent power-The separation of the rms current and voltage into fundamental and harmonic terms resolves the apparent power in the following manner:

$$\begin{aligned} S^2 &= (VI)^2 = \left(V_1^2 + V_H^2\right) \cdot \left(I_1^2 + I_H^2\right) = \\ &= (V_1 I_1)^2 + (V_1 I_H)^2 + (V_H I_1)^2 + (V_H I_H)^2 = S_1^2 + S_N^2 \end{aligned} \tag{26}$$

$$S_N = \sqrt{S^2 - S_1^2} \tag{27}$$

is the nonfundamental apparent power, and is resolved in the following three distinctive terms:

$$S_N^2 = D_I^2 + D_V^2 + S_H^2 \tag{28}$$

The *current distortion power* is:

$$D_I = V_1 I_H = S_1 (THD_I) \tag{29}$$

The *voltage distortion power* is:

$$D_V = V_H I_1 = S_1 (THD_V) \tag{30}$$

The *harmonic apparent power* is:

$$S_H = V_H I_H = S_1 (THD_I)(THD_V) \tag{31}$$

$$S_H = \sqrt{P_H^2 + D_H^2} \tag{32}$$

The *harmonic distortion power* is:

$$D_H = \sqrt{S_H^2 - P_H^2} \tag{33}$$

The *nonactive power* is:

$$N = \sqrt{S^2 - P^2} \tag{34}$$

This power lumps together both fundamental and nonfundamental nonactive components. In the past, this power was called *fictitious power*. The nonactive power N shall not be confused with a reactive power. Only when the waveforms are perfectly sinusoidal, $N = Q_1 = Q$.
The *fundamental power factor* is:

$$PF_1 = \cos\theta_1 = \frac{P_1}{S_1} \tag{35}$$

4. Calibration of the virtual power quality analyzer

IEC 61000-4-7, [3], beside the guidance on harmonics measurement and quality analysers design, specifies also the maximum admissible errors in measurement, as it is shown in Table I.

Table I-Accuracy for Voltage, Current and Power Measurement, Instrument class I

Measurement	Conditions	Maximum error
Voltage	$U_m \geq 1\% U_{nom}$ $U_m < 1\% U_{nom}$	$\pm 5\%\ U_m$ $\pm 0{,}05\%\ U_{nom}$
Current	$I_m \geq 3\% U_{nom}$ $I_m < 3\% U_{nom}$	$\pm 5\%\ I_m$ $\pm 0{,}15\%\ I_{nom}$
Power	$P_m \geq 150$ W $P_m < 150$ W	$\pm 5\%\ P_{nom}$ $\pm 1{,}5$ W

Table II. – NI 9225 accuracy specifications

Measurement conditions	Percent of reading (Gain Error)	Percent of Range (Offset Error)
Calibrated max (-40 °C to 70 °C)	±0,23%	±0,05%
Calibrated typ (25 °C, ±5 °C)	±0,05%	±0,008%
Calibrated max (25 °C, ±15 °C)	±0,084%	±0,016%
Uncalibrated max (-40 °C to 70 °C)	±1,6%	±0,66%
Uncalibrated typ (25 °C, ±5 °C)	±0,4%	±0,09%

The producer National Instruments delivers calibrated input modules NI 9225 for voltage measurements and NI 9227 for four current measurements. The producer has also specified the technical characteristics of the input modules and the accuracy for different conditions. In Table II the accuracy specifications of the NI 9225 input voltage measurement module given by NI are shown.

A. Calibration procedure

The calibration and verification of the virtual power analyser was performed using a procedure developed in the Metrological Laboratory for Electromagnetic Quantities of the Faculty of Electrical Engineering and Information Technologies-Skopje, based on the direct measurement of the standard value. The calibration arrangement is shown on Fig. 4.

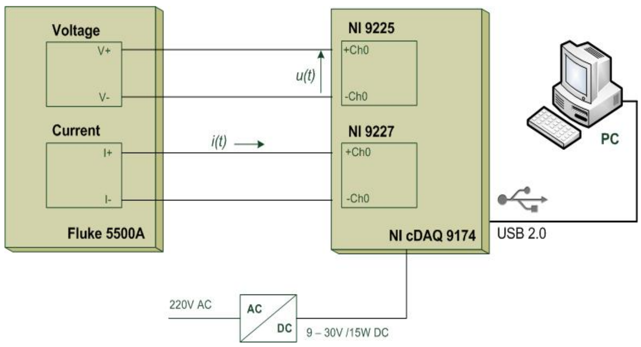

Fig. 4 Calibration arrangement

B. Laboratory Environment

The conditions in the calibration laboratory were controlled and registered. The temperature T=(23±10) ºC, relative humidity R≤70%, the room is protected against electromagnetic radiation.

C. Calibration Equipment

For calibration of the virtual instrument, the laboratory calibrator FLUKE 5500A has been used. The calibrator is a multifunction programmable source which generates reference values of DC voltage and current, AC sinewave and nonsinewave voltage and current, DC and AC power, voltage and current distorted with harmonics, with sinusoidal form at different frequencies. The errors and the drift with the time and temperature for all the listed quantities, outputs of the calibrator FLUKE 5500A, are given in the calibrator specifications and calibration certificate.

D. Traceability

Metrological traceability to the national standards is achieved by calibration of the FLUKE 5500 at the National Bureau of Metrology of R. Macedonia.

E. Estimation of the Measurement Uncertainty

Measurement uncertainty is estimated according the ISO/IEC Guide of the Expression of Uncertainty in

Measurement [8], mainstream procedure. Four independent sources of uncertainty were considered for modelling the measurement error of the virtual instrument: the repeatability of the instrument, the resolution of the instrument, the uncertainty of the value of the standard, and the drift of the standard.

The model of the measurement error is:

$$E_X = X_I \pm \Delta X_I - X_S - \Delta X_S \quad (36)$$

where: X_I – the instrument reading, ΔX_I - correction due to the resolution of the instrument, X_S - the value of the standard, and ΔX_S - the drift of the standard.

The calibration measurement result X_i is characterized by the mean $\overline{X}$, standard deviation σ and the student probability distribution function (pdf). The correction due to the resolution of instrument is characterized by the resolution value, standard deviation and the rectangular pdf. The value of the standard is characterized by nominal value, standard uncertainty and normal pdf. The correction due to the drift of the standard is characterized by ΔX_S, the standard deviation and rectangular pdf. The combined uncertainty of the measurement error is:

$$u_c^2(E_x) = \sqrt{u^2(X_I) + u^2(\Delta X_I) + u^2(X_S) + u^2(\Delta X_S)} \quad (37)$$

F. *Calibration results*

The virtual instrument was calibrated for all measuring quantities by programming the calibrator outputs and measurement under condition of repeatability. A part of calibration results are given in Tables III-V.

Table III. – Voltage calibration

U_{ref} [V]	U_{meas} [V]	THD [%]	ξ [%]
1	0,99973	0,012	-0,027
10	9,9974	0,008	-0,026
100	99,976	0,010	-0,024
200	199,95	0,012	-0,025
230	229,95	0,012	-0,022
250	249,95	0,013	-0,020

Table IV. – Current calibration

I_{ref} [A]	I_{meas} [V]	THD [%]	ξ [%]
0,01	0,01005	0,186	0,500
0,1	0,10006	0,019	0,060
0,5	0,50072	0,013	0,144
1	1,0006	0,011	0,060
2	2,0004	0,012	0,020
3	3,0048	0,044	0,160
4	4,0046	0,032	0,115
5	5,0047	0,029	0,094

Table V. – Power calibration

U_{ref} [V]	I_{ref} [A]	P [W]	PF	P_{meas} [V]	ξ [%]
230	0,1	23	0,99994	23,007	0,030
230	0,5	115	1,00000	115,13	0,113
230	1	230	1,00000	230,08	0,035
230	2	460	1,00000	459,97	-0,007
230	3	690	1,00000	690,96	0,139
230	4	920	1,00000	920,85	0,092
230	5	1150	1,00000	1150,7	0,061

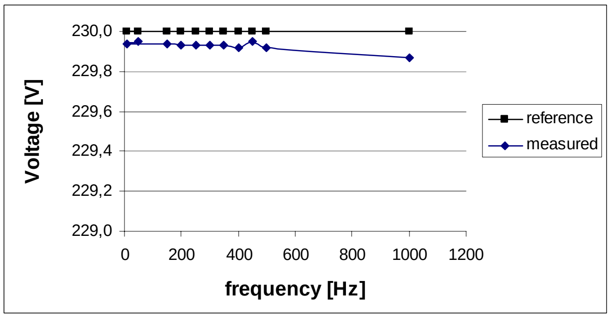

Fig. 5 Voltage frequency characteristic

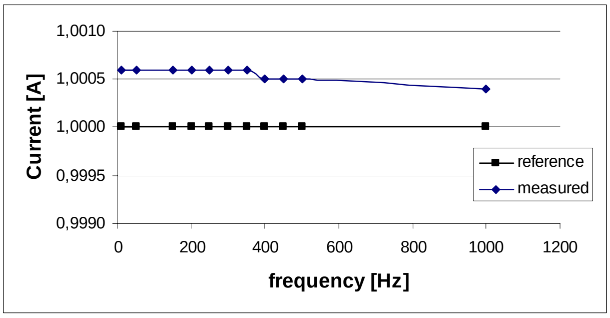

Fig. 6 Current frequency characteristic

The complete calibration results of all the measurement quantities and all the ranges, which because of space limits cannot bi given in the paper, have shown that the virtual instrument for measurement of power quality is very accurate and precise instrument.

5. Case study-measurement results

With the developed and calibrated instrument seria of measurements of the power quality characteristics near different disturbing sources are realized. The measurement results of two different lighting technologies are shown below in the paper as case studies: ECO Energy saving light and LED light.

A. *ECO Energy saving light*

The ECO Energy saving light generation of harmonics is illustrated in Fig. 7 by the distortion of the current sinusoidal form, and by the harmonic spectrum.

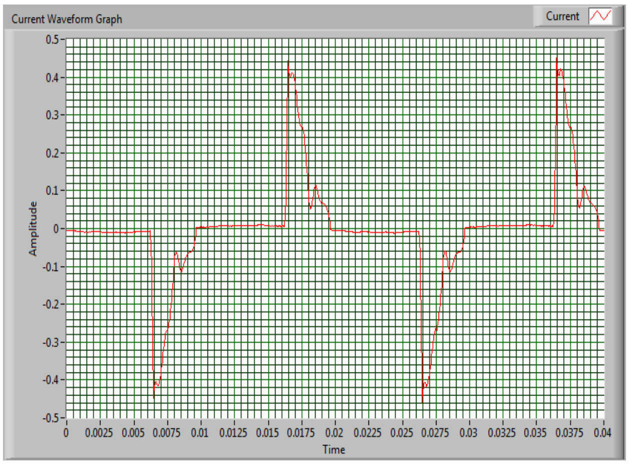

Fig. 7. Current waveform graph of ECO Energy saving light, THDI=113,12%

The measurement of power characteristics of the ECO bulb is shown on the Fig. 8.

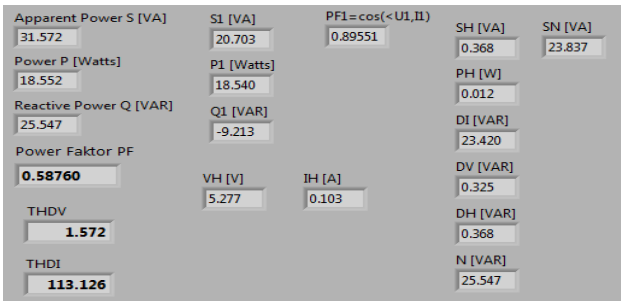

Fig. 8 Energy saving light power characteristics

B. LED street light

The LED street light generation of harmonics is illustrated in Fig. 9.

Fig. 9 Current waveform graph of LED light, THDI=15.03%

The measurement of power characteristics of the LED street light is shown on the Fig. 10.

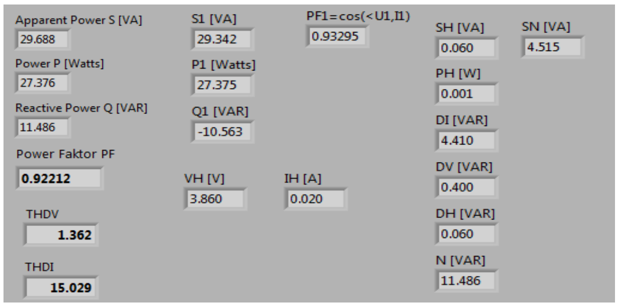

Fig. 10 Power characteristics of the LED street light

The comparison of the presented two bulbs shows that the ECO Energy saving light is more severe source of distortion and has worse power characteristics than the LED light.

6. Conclusion

The developed virtual power quality analyzer is shown to be a useful tool for power quality monitoring and analysis of the sources of disturbances and the state of the system. The instrument has been calibrated and verified with the laboratory calibrator FLUKE 5500A, which ensures precise measurements and traceability to the National Metrology Institute (Bureau of Metrology of R. Macedonia). The power quality analyzer enables flexibility, upgrading and improvement according to the future needs for monitoring and analysis of the power quality.

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