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Design and Evaluation of Computer-based Electrical Power Quality Signal Generator

Milan Simić[1], Zivko Kokolanski[2], Dragan Denić[1], Vladimir Dimcev[2], Dragan Živanović[1], Dimitar Taskovski[2]

[1]*University of Niš, Faculty of Electronic Engineering, Niš, Serbia, milan.simic@elfak.ni.ac.rs*
[2]*Ss. Cyril and Methodius University in Skopje, Faculty of Electrical Engineering and Information Technologies, Skopje, Macedonia*

***Abstract*—Electrical power quality signal generator, capable of reproducing the power quality disturbances in accordance with European standard EN50160, is presented in this paper. Signal generator is divided in two parts: LabVIEW based virtual instrumentation software for defining the disturbance parameters and hardware electronics for signal generation (data acquisition card and power amplifier). The paper focus is on the design of power amplifier for scaling the data acquisition card output voltage level to the nominal power line voltage (230 V). The signal generator can be used for generation of reference signals useful for testing the power quality measuring instruments and various algorithms for power quality disturbance detection. In such manner, this PC based signal generator can be used as suitable and cost effective alternative to the instruments for testing the power quality meters and analyzers. According to the relevant document - ISO Guide to the Expression of Uncertainty in Measurement, for detailed metrological assessment of developed signal generator, calculation and presentation of measurement uncertainty budget is performed.**

***Keywords*—electrical power quality, signal generator, power amplifier, virtual instrument, measurement uncertainty**

I. Introduction

DEGRADATION of the optimal power quality (PQ) can be caused by various problems and signal disturbances in electrical power distribution networks. Signal disturbances, present in form of voltage variations or high-order signal harmonics, directly worsen the energy efficiency in electrical power production, distribution and consumption. The increased concern for such problems in power quality, which is indicated in recent years, primarily is caused by limitations of natural energy resources necessary for power production. This is followed by widespread using of the renewable energy resources [1, 2]. Hence, power quality problems became very important and significant topic. In order to provide customer protection, optimal power quality level is defined according to relevant international standards and regulations [3]. European standard EN 50160 defines voltage characteristics of the public power distribution systems, for normal operating conditions. The required power quality level is determined by reference nominal values and acceptable limits of basic power quality parameters and typical network disturbances. Relevant information, necessary for power quality assessment, can be provided by measurement and processing of quality parameters at specific locations in power distribution network.

Various types of devices and equipment for measurement and software supported processing of standard PQ parameters are available on the market. These measurement instruments are developed to perform continuous monitoring of power supply quality inside power distribution networks. Instruments for PQ measurement can be used as single devices located at selected points in distribution network. Alternatively, several separated devices can be combined into distributed measurement system for monitoring of PQ, including measurement, recording and analysis of standard quality parameters and disturbances [4, 5].

Having in mind the challenges of the modern smart grids and great importance of PQ problems, special attention is paid to development of sophisticated and reliable microprocessor-based measurement systems for PQ monitoring. In the last decade especially attractive are so called ‘‘virtual instruments’’, which are well suited for development of flexible computer-based measurement systems. Generally, the virtual instruments can be successfully used for research and scientific purposes. A lot of scientific papers on virtual instrumentation for PQ analysis (both for measurement or signal generation) have being published [6-11]. However, usually less attention is paid to the signal amplification, which is very important for the practical implementation of virtual PQ signal generators.

In order to satisfy the specified level of the measurement accuracy and basic characteristics, devices for measurement of PQ parameters must be followed by appropriate metrological traceability chain. Reference instruments, such as voltage and current calibrators, are available in the various functional and constructive solutions. Such instruments are sources of the reference waveforms with high accuracy levels, which correspond to the secondary standards, laboratory and industrial standards in metrological traceability chain. Also, some commercial calibration instruments are developed for specific types of PQ meters. Such commercial calibration instruments are relatively expensive and therefore unavailable to many scientific researchers. Significant limitation of such devices is closed functional architecture, developed according to the relevant quality standards. Due to this limitation, such instruments are not flexible and hardly adaptable to meet the requirements of specific problems. The virtual instrument, presented in this paper, is capable of reproducing the PQ disturbances in accordance with the European standard EN50160. This solution is easily adaptable to various practical requirements, for example data logging, random PQ sequence generation and upgrading of some recently defined network disturbances [12].

The developed signal generator can be used as a source of reference signals for testing instruments for measurement of quality parameters and network disturbances, including testing of various software supported algorithms for PQ disturbance detection [13, 14]. Evaluation of the measurement uncertainty components is also very important segment necessary for detailed metrological characterization of developed computer-based generator. Consequently, procedure for evaluation of measurement uncertainty components, performed according to relevant standard - ISO Guide to the Expression of Uncertainty in Measurement [15], is given in the final section of this paper.

II. Virtual Instrument for Generation of Standard PQ Disturbances

Generator of sinusoidal voltage waveforms for standard PQ disturbances is based on virtual instrumentation concept, including LabVIEW software platform and data acquisition card NI PCIe 6343. Virtual instrument (VI) is divided in two segments: a graphical user interface (front panel) and program code (block diagram), both strongly interlinked between each other. Basic purpose is generation of reference voltage signals with special functions for simulation of standard PQ network disturbances [16, 17]. Generally, this virtual instrument enables generation of three-phase signals. Currently, signal amplifier is developed for amplification of the generated one-phase voltage waveform, but this solution can be simply multiplied in simetrical manner in order to simulate a three phase system. Some basic functions provided by virtual instrument for PQ signal generation are:

- definition of nominal signal amplitude and frequency values,
- definition of signal sample rate and duration of final test sequence,
- generation of noise (with Gaussian distributed amplitude),
- variation of nominal signal frequency value and slow amplitude fluctuations,
- slow variation of signal amplitude value with defined frequency of variation,
- definition of DC offset, voltage swell and voltage sag,
- definition of high-order signal harmonic components with up to 50 individual defined harmonics,
- generation of some special types of disturbances (flicker, burst transients, short voltage oscillation).

LabVIEW front panel of signal generator for presentation of sinusoidal voltage waveforms, with four different examples, is given in Fig. 1. Definition and simulation of voltage waveforms, with specified levels of standard PQ disturbances, can be performed directly inside the control panel and block diagram of LabVIEW virtual instrument. Each type of signal disturbances, for example voltage swell, voltage sag and high-order signal harmonics, can be defined and generated using separate functional segments. Individual disturbances can be combined and unified in the form of final complex sequence, according to the requirements of European PQ standard EN 50160 [3].

Separated segment of control functions in the virtual instrument is used for selection and adjustment of specific amplitude levels related to individual high-order harmonic components. Control panel of LabVIEW virtual instrument, presented in Fig. 1, shows four examples of sinusoidal voltage waveforms, generated with various levels of high-order signal harmonic components. Content of specific high-order harmonics can be precisely determined by number of control knobs for regulation of harmonic amplitude levels. Presented voltage waveforms are generated with nominal signal frequency value of 50 Hz and normalized RMS voltage value of 5.5 V. In order to be more realistic in generation of voltage waveforms, each disturbance can be defined by the following parameters: nominal frequency variations, signal DC offset, amplitude fluctuations, start and stop times of specific disturbance, rising and falling times of signal disturbances, etc.

Some additional classes of network disturbances can be also generated by the described signal generator. These characteristic disturbances are: flicker generated as slow variation of signal amplitude level, voltage interruption that can be defined as one special type of voltage sag, burst transients and short voltage oscillation caused by the presence and influence of higher signal harmonics.

Block diagram developed in LabVIEW programming environment (software code), corresponding to the previously described virtual instrument for generation of PQ signal disturbances, is presented in Fig. 2.

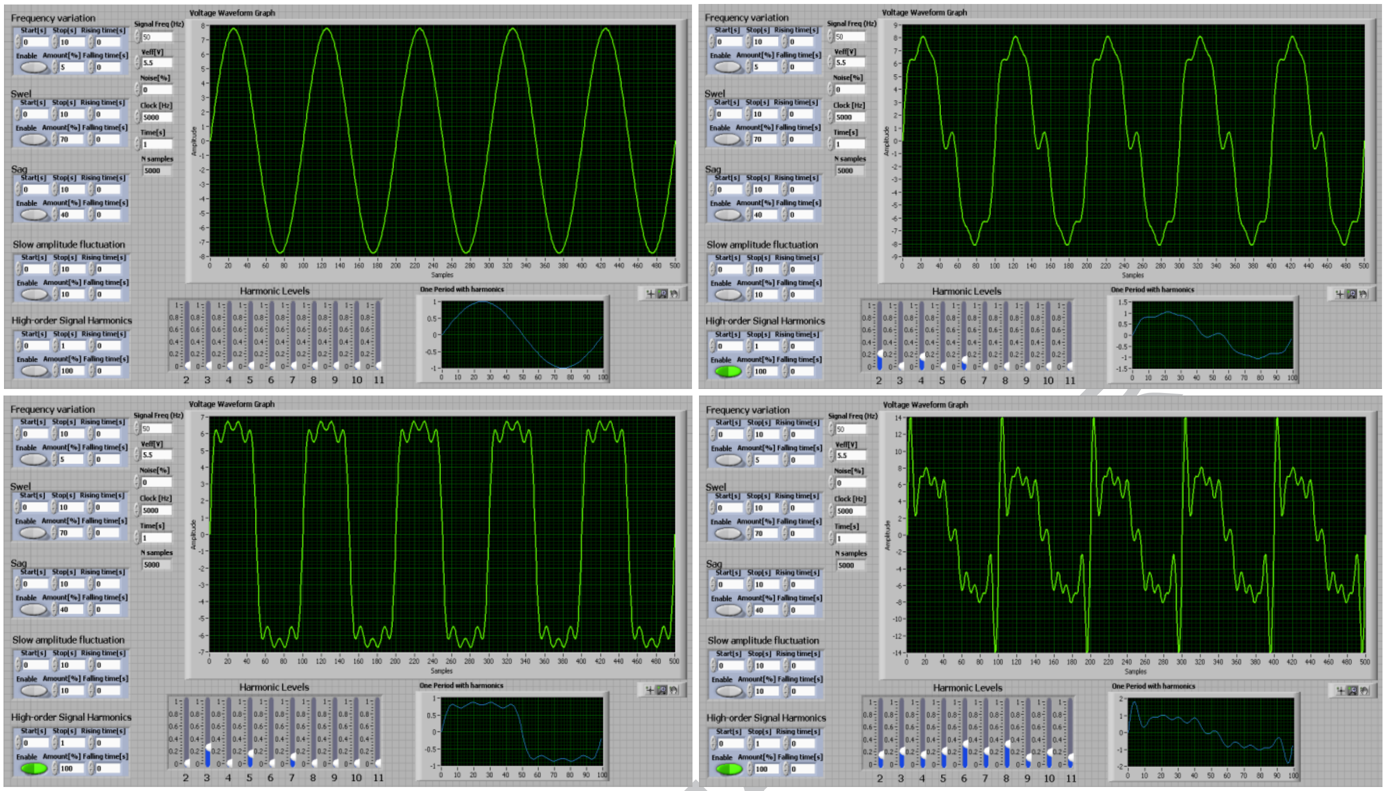

Figure 1. Control front panels of LabVIEW signal generator (voltage test waveforms with various levels of high-order signal harmonics)

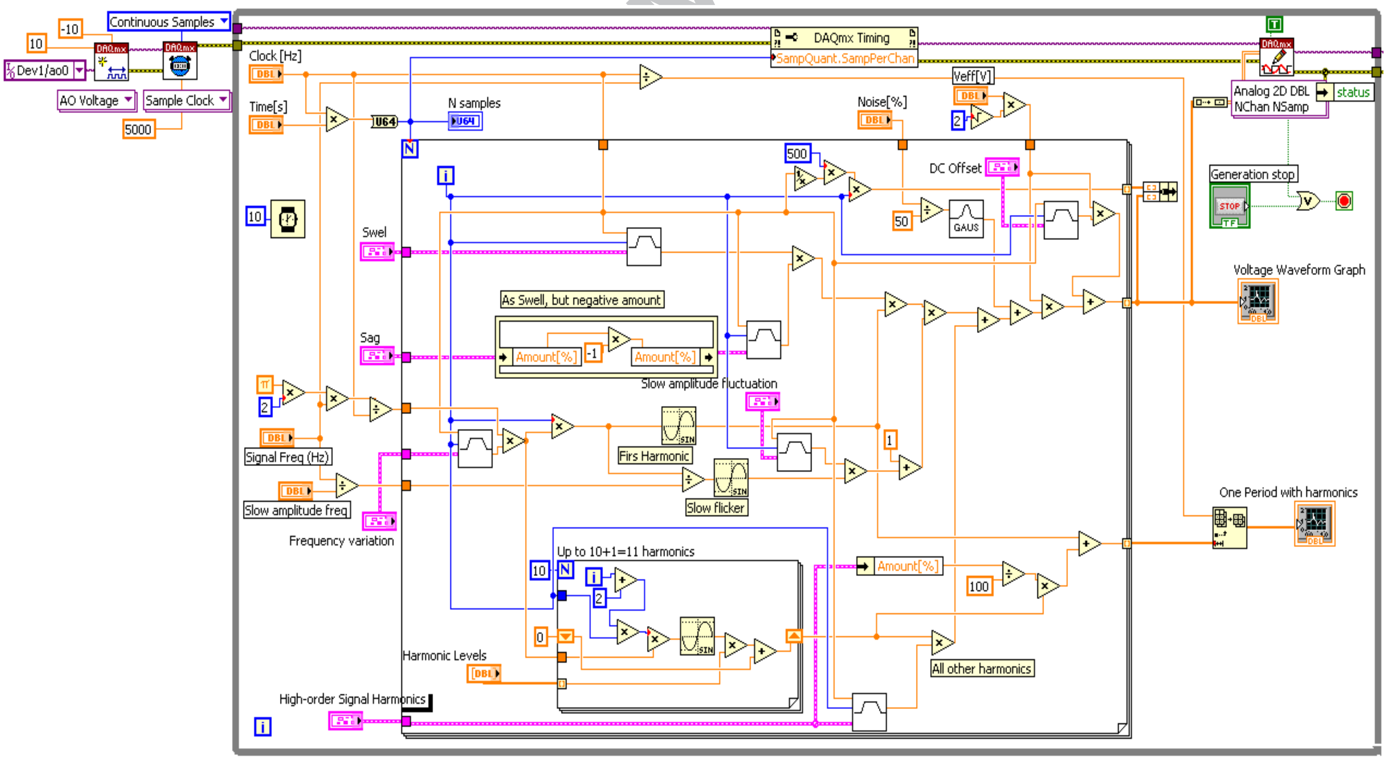

Figure 2. Block diagram in LabVIEW environment (executive software code) – virtual instrument for generation of PQ signal disturbances

III. Power Amplifier Design

The signal generated (simulated) by the virtual instrument is usually physically reproduced by using a computer-based data acquisition (DAQ) card containing a digital to analog (DA) converter. The DA converter output signal is usually standardized to a given voltage level, typically up to ±10 V. Such voltage levels are not directly applicable to test power quality meters and have to be amplified to the nominal power line voltage of 230 V (or 110 V) prior the measurements. A dedicated data acquisition cards with "high voltage" outputs are also available, but they are usually relatively expensive. The aim of this paper is to address the key parameters in the design phase in order to implement a low-cost and full-performance PQ signal generator.

The block diagram of the realized PQ signal amplifier is given in Fig. 3.

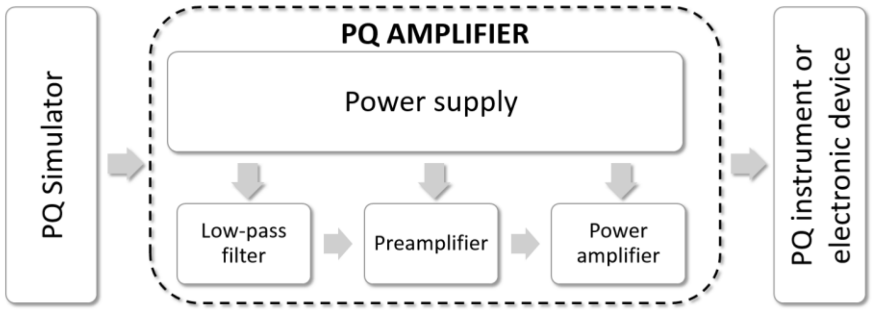

Figure 3. Block diagram of the PQ signal amplifier

The simulated signal with the LabVIEW software can be reproduced by any standard DAQ card with analog output channels. However, the DAQ card should meet some implementation related requirements. Namely, it must have good-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 maximal harmonic frequency. According to the standard EN50160 [3] (up to 50th harmonic), the minimum sampling frequency is 5 kHz. However, in practice the sampling frequency should be higher to maintain the accuracy of the higher harmonics.

The generated signal with the DAQ card is amplified by an amplifier (given in Fig. 3), which amplifies the signal to the nominal power line level of 230 V. To do so, several analog signal processing modules are used: preamplifier (to amplify the input signal to a given reference level), low pass filter (to restrict the input signal bandwidth and eliminate noise), power amplifier (to amplify the signal to nominal power line level, limit the input voltage level, and increase the load current capability).

A. Low-pass antialiasing filter

The filters are characterized by several parameters: width of the pass band, attenuation in the stop band, cut-off frequency and filter order. Every filter type has its own unique properties. The Bessel filter has the most linear phase-frequency characteristics, Butterworth filter have maximally flat pass band and Chebyshev filter have the highest attenuation in the stop band but also ripples in the pass band. When designing an anti-aliasing filter it is necessary to consider the -3 dB attenuation at the cut-off frequency. If this is not taken into account, the signal will be attenuated at higher frequencies (harmonics) and the error caused by the filter at the cut-off frequency will be around 30%. Therefore, to control the errors caused by the non-ideal shape of the amplitude-frequency characteristics in [18] a CFM (Cut-off Frequency Multiplier) parameter is proposed. The CFM parameter defines a segment of the pass band where the errors caused by the difference between the real and the ideal filter transfer characteristics are controlled to certain defined level (e.g. 0.1%). It is important to note that the CFM value decrease with the filter order. However, the value of CFM stabilizes for a filter order higher that four and further increase carry benefit only in the attenuation in the stop band. Hence, if a Butterworth fourth order filter is designed, the value of the CFM parameter will be 2.18. This means that the filter cut-off frequency should be 2.18 times higher than the frequency of the highest harmonic in the signal spectrum. Hence, a fourth order Butterworth low-pass filter in a Sallen-key configuration (realized as a cascade of two two-pole filters) was designed. The realized filter is given in Fig. 4 (left side).

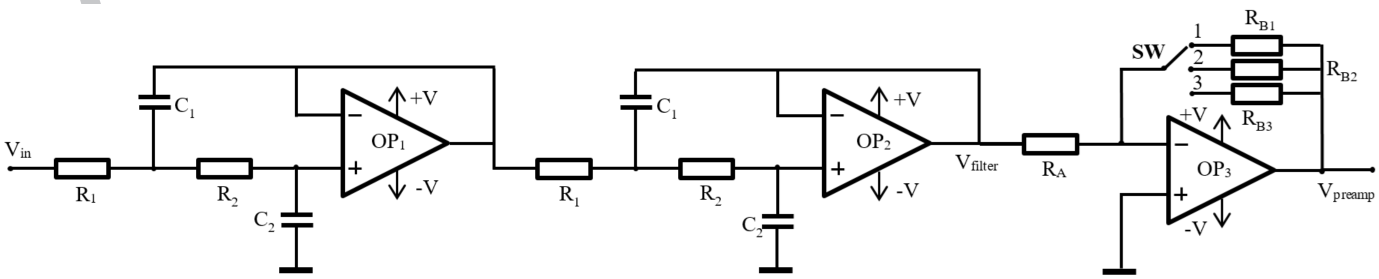

Figure 4. Electrical circuit of an active unity gain Butterworth fourth order low-pass filter (left) and inverting preamplifier (right)

When designing a filter we must choose appropriate quality factor Q and define the cut-off frequency f_c. Considering that 50^{th} voltage harmonic (f_{50} =2.5 kHz) has to be analyzed, the cut-off frequency of the filter is 5.45 kHz (CFM=2.18). The cut-off frequency is defined as:

$$f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}, \tag{1}$$

whereas the filter quality factor is:

$$Q = \sqrt{\frac{R_1 R_2 C_1 C_2}{C_2\sqrt{R_1 + R_2}}}, \tag{2}$$

The Q factor determines the height and the width of the peak in the frequency response of the filter. As this parameter increases, the filter will tend to "ring" at a single resonant frequency near f_c. In order to implement a second order Butterworth filter the Q factor should be $1/\sqrt{2}$. Hence, the passive components R_1, R_2, C_1 and C_2 are calculated according the values for f_c and Q by using (1) and (2).

B. Preamplifier

In the proposed solution, the preamplifiers role is to amplify the input signal (coming from the DA converter) to a standardized reference level. The idea is to design an amplifier capable of reproducing the power line voltage with any standard DA converter output voltage levels. This was achieved by setting the maximum output preamplifier voltage to a reference level of ± 10 V. Hence, the preamplifier must have variable gain in discrete steps (4, 2, and 1 times) in order to accept different standard input voltage levels (± 2.5 V, ± 5 V and ± 10 V), respectively. Such solution can be easily implemented with a classical operational amplifier in inverting or non-inverting configuration and with a gain selector switch. The realization of the preamplifier block is given in Fig. 4 (right). The gain of the preamplifier is determined by the switch SW, which selects one of the resistors R_{B1}, R_{B2} or R_{B3}. The output signal can be then expressed as:

$$V_{preamp} = -\frac{R_{B_{SW}}}{R_A} V_{filter}\Big|_{SW\in\{1,2,3\}}, \tag{3}$$

where V_{filter} is the output signal of the anti-aliasing filter. The negative sign in (3) denotes that the phase of the input signal is inverted, which is expected having in mind the inverting configuration of the operation amplifier.

All operational amplifiers in the filter and the preamplifier sections (OP1 to OP3) are supplied with a symmetrical power supply of ±V. In practice, these sections were realized by using a low-noise and low-offset operational amplifiers OP07 [19].

C. Power amplifier

The power amplifier role is to amplify the input signal (standardized to a V_{ref} = ± 10 V) to the power line voltage level. However, in order to be able to generate voltage swells, the power line voltage level should be placed near the middle of the DA converter analog output voltage range. The electrical circuit of the power amplifier is given in Fig. 5.

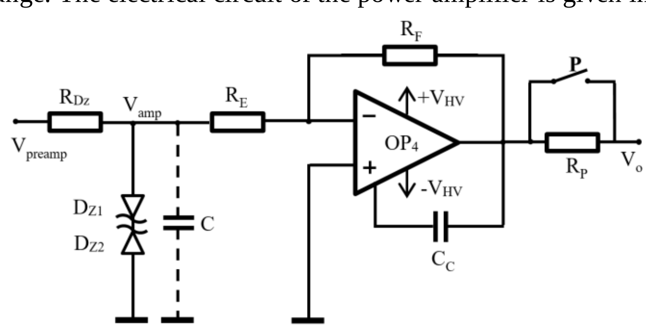

Figure 5. Electrical circuit of the power amplifier with limiter

The input stage of the power amplifier consists of a voltage limiter formed by the Zener diodes D_{Z1}, D_{Z2} and the resistor R_{Dz}. The limiter ensures that the input voltage of the power amplifier doesn't exceed a given maximal value. This module is very important considering that the gain of the power amplifier is relatively high, and thus, it can cause saturation or even damage in case of input voltage transients (e.g. from the power supply). The resistor R_{DZ} limits the inverse current through the Zener diodes and is calculated according the following parameters: the reference voltage level, the Zener diode breakdown voltage, and the Zener diode power. In case when a voltage transient (positive or negative) higher than the maximal input reference level occurs, one of the Zener diodes is forward and the other one inversely polarized. In such case, the input voltage of the power amplifier is limited to:

$$V_{amp} = \left(V_{DZ_F} + V_{DZ_{BR}}\right) \leq V_{ref} ,$$

(4)

where V_{DZF} is the forward bias voltage, V_{DZBR} is the breakdown voltage of the Zener diodes, and V_{ref} is the maximal allowed reference level (±10 V in this case). On the other hand, when inversely polarized, the Zener diodes can inject a significant amount of noise at the input of the power amplifier and worsen its metrological performances. This can be reduced by placing the capacitor C in Fig. 5 in parallel with the diodes. The resistor R_{DZ} and the capacitor C in this case form a passive first order low-pass filter that reduces the noise effects. The cut-off frequency of the filter has to be well above the PQ generator pass-band (which is CFM times higher than the frequency of the 50th harmonic of the power line frequency). In the current realization, a first order passive RC filter with a cut-off frequency of 22.5 kHz was realized.

The power amplifier scales the preamplifier output signal to the nominal power line voltage level. The gain of the power amplifier is defined as:

$$A_{PA} = \frac{V_o}{V_{amp}} = -\frac{R_F}{R_E} ,$$

(5)

where V_{amp} is the input, and V_o the output voltage of the power amplifier. Having in mind that in the current realization V_o = ± 400 V, and V_{amp} = V_{ref} = ± 10 V, the gain of the power amplifier is A_{PA} = 40 times. Hence, the values of the resistors R_F and R_E are determined according A_{PA}. As it can be seen from Fig. 5, the power amplifier is in inverse configuration and shifts the phase of the input signal. However, the preamplifier and the power amplifier compensate the phase (by double inversion), so the output signal of the amplifier is finally in phase with the input signal of the antialiasing filter.

The power amplifier was designed by using APEX PA97 [20] high voltage operational amplifier (OP4 in Fig. 5). The amplifier is capable of delivering 10 mA at 500 V (power of 5 W), which is sufficient to test PQ meters or to supply some low-power electronic devices. The power amplifier is supplied with symmetrical power supply of V_{HV} = ±410 V. The capacitor C_C serves as a decoupling capacitor which prevents amplifier oscillations. Finally R_p is a short-circuit protection resistor which can be removed by the switch P after safe wiring of the PQ amplifier. It is important to bridge R_p during measurements because it increases the output resistance of the amplifier and decrease the signal accuracy.

D. Experimental verification of PQ signal generator

Developed signal generator is experimentally verified by using the PQ analyzer Fluke 435. Reference voltage waveforms, generated by the computer-based signal generator with various levels of harmonic disturbances, are sent directly to the voltage inputs of quality analyzer Fluke 435. Photo of experimental system including PQ signal generator and reference instrument Fluke 435 is given in Fig. 6.

Standard Universal Serial Bus (USB) communication interface enables direct communication between instrument Fluke 435 and computer, therefore obtained measurement results can be easily transferred to the computer, recorded and processed. Four examples of voltage waveforms from PQ signal generator with various levels of signal harmonics, recorded on graphical display of reference instrument Fluke 435, are given in Fig. 7. Specific waveforms are corresponding to the voltage signals generated by LabVIEW virtual instrument and previously presented in Fig. 1.

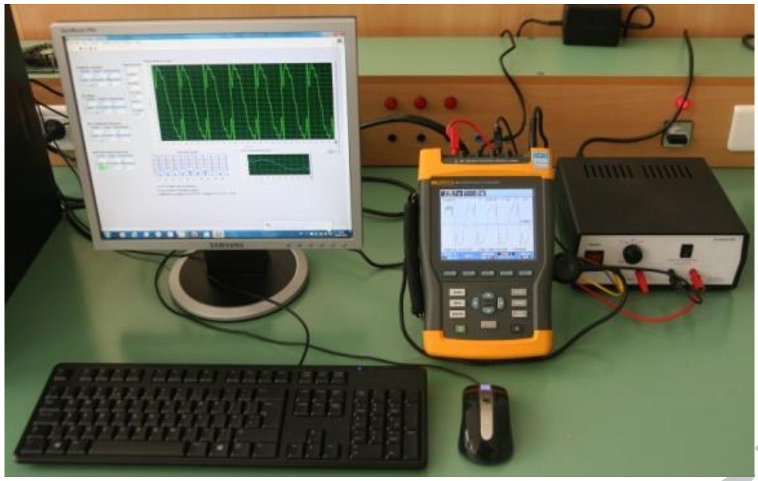

Figure 6. Experimental system for verification of computer-based PQ signal generator

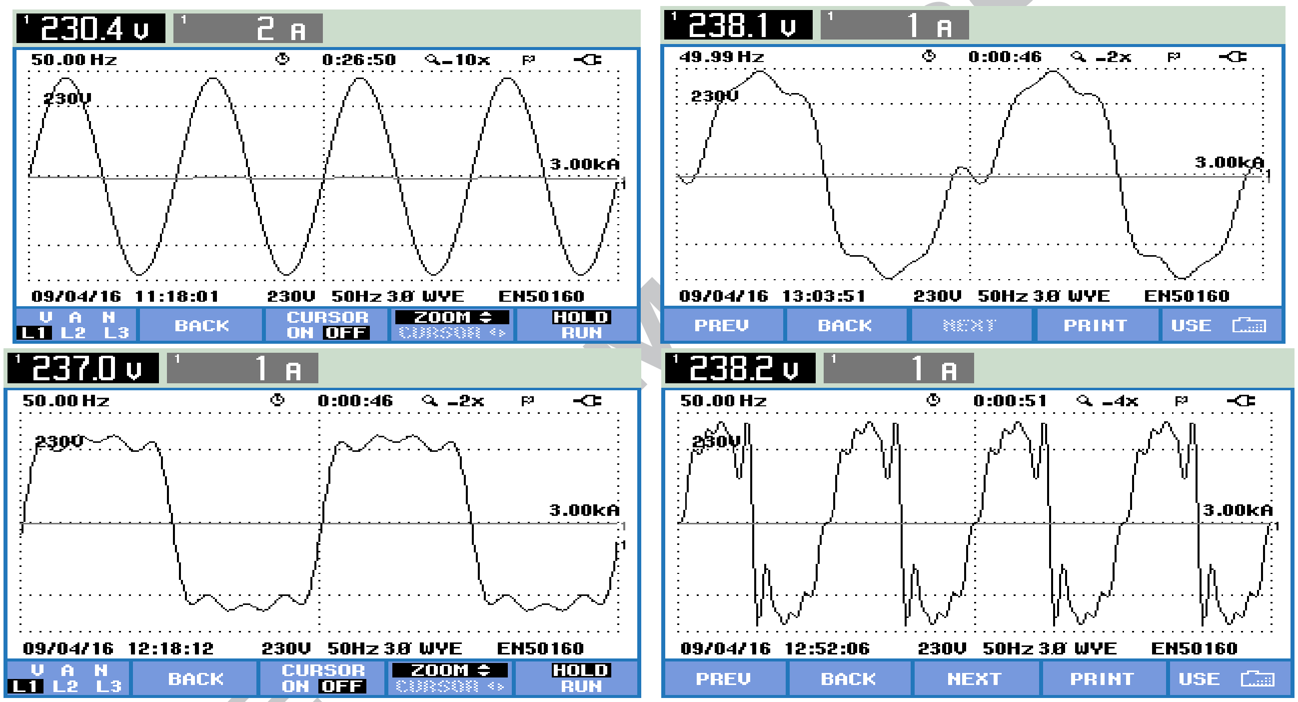

Figure 7. Voltage signals with harmonic disturbances recorded on display of reference instrument - PQ analyzer Fluke 435. Ideal sinusoidal voltage (upper left), signal with even harmonics (upper right), signals with odd harmonics (lower left), signal with transients (lower right).

E. Metrological characteristics of PQ amplifier

For detailed metrological characterization, both amplitude-to-amplitude and amplitude-to-frequency characteristics of the preamplifier (preamplifier and filter) module were measured. The amplitude-to-amplitude characteristics were measured for all three input signal ranges ± 2.5V, ± 5V and ± 10V. The preamplifier signal amplification in each measurement was 4, 2 and 1 times, respectively. The input signal was obtained from high quality signal source - calibrator Fluke 5500A [21], and the output signal was measured with a 6 ½ digit precision digital multimeter Fluke 8846A [22]. The measurement results are given numerically in Table I, and graphically in Fig. 8. Hence, it can be seen that the transfer characteristics of the preamplifier module have a very low offset, nonlinearity and gain component in all input signal ranges. This is mainly due to the performances of the operational amplifier, and the zero-offset voltage trimming with a built in multi-turn resistors.

TABLE I

PREAMPLIFIER AMPLITUDE-TO-AMPLITUDE CHARACTERISTICS – OBTAINED MEASUREMENT RESULTS FOR INPUT VOLTAGE RANGES 2.5V, 5V AND 10V

Range 2.5V	Range 5V	Range 10V	Range 2.5V	Range 5V	Range 10V
V_{I1} [V]	V_{I2} [V]	V_{I3} [V]	V_{O1} [V]	V_{O2} [V]	V_{O3} [V]
2.5	5	10	- 10.006	- 10.0028	- 9.988
2.25	4.5	9	- 9.0057	- 9.0139	- 8.9915
2	4	8	- 8.0054	- 8.0123	- 7.9941
1.75	3.5	7	- 7.0051	- 7.0108	- 6.997
1.5	3	6	- 6.0047	- 6.0093	-5.999
1.25	2.5	5	- 5.0042	- 5.0078	- 5.0007
1	2	4	- 4.0036	- 4.0063	- 4.001
0.75	1.5	3	- 3.0029	- 3.0048	- 3.0022
0.5	1	2	- 2.0021	- 2.0033	- 2.00161
0.25	0.5	1	- 1.00125	- 1.00177	- 1.0009
0	0	0	- 0.00039	- 0.199 m	- 0.1054m
-0.25	-0.5	-1	1.0049	1.0041	1.00079
-0.5	-1	-2	2.00147	2.00303	2.00161
-0.75	-1.5	-3	3.00233	3.00463	3.0022
-1	-2	-4	4.00314	4.00623	4.0024
-1.25	-2.5	-5	5.0037	5.00778	5.002
-1.5	-3	-6	6.0042	6.0093	6.0001
-1.75	-3.5	-7	7.0046	7.0107	6.998
-2	-4	-8	8.0047	8.0121	7.995
-2.25	-4.5	-9	9.0046	9.0133	8.990
-2.5	-5	-10	10.0044	10.0143	9.987

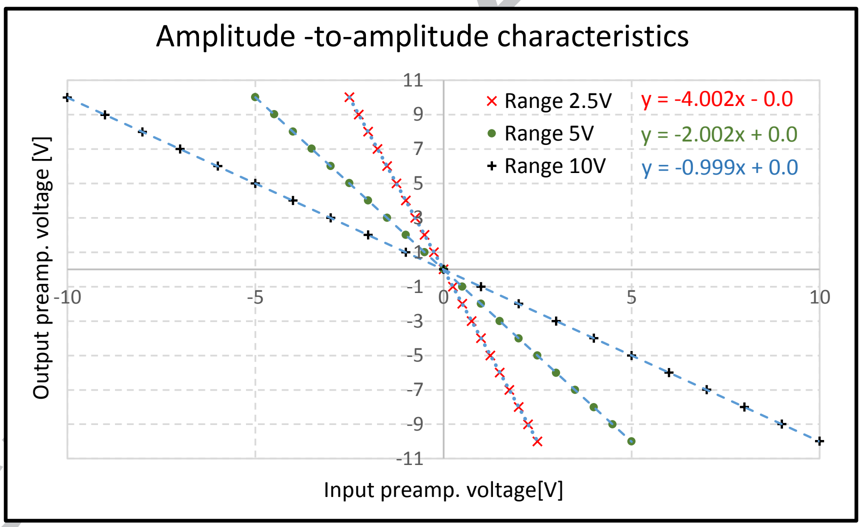

Figure 8. Preamplifier amplitude-to-amplitude characteristics for input voltage ranges ± 2.5V, ± 5V and ± 10V

The preamplifier amplitude-to-frequency characteristics was measured by using the same measurement setup as with the amplitude-to-amplitude characteristics, but within the input signal frequency range from 10Hz to 50kHz. The measurements were performed for three different values of the input voltage range ± 2.5V, ± 5V and ± 10V. But, in this case, the input voltage was set to the constant value of 1 V. The attenuation of the preamplifier at a given frequency is presented in Table II and in Fig. 9. It can be seen that, as expected, the pass band is relatively flat, whereas the cut-off frequency is around 6 kHz. The small deviation of the cut-off frequency comparing to the theoretical calculations is due to the passive components mismatch and tolerances.

TABLE II
PREAMPLIFIER AMPLITUDE-TO-FREQUENCY CHARACTERISTICS – OBTAINED MEASUREMENT RESULTS AND ATTENUATION FOR INPUT VOLTAGE RANGES 2.5V, 5V AND 10V

	Range 2.5V	Range 5V	Range 10V	Range 2.5V	Range 5V	Range 10V
f_I [Hz]	V_{O1} [V]	V_{O2} [V]	V_{O3} [V]	B_1 [dB]	B_2 [dB]	B_3 [dB]
10	3.99	1.997	0.999	12.019	6.008	-0.009
30	3.9956	1.9996	1.0003	12.032	6.019	0.003
50	3.9959	1.9997	1.0004	12.032	6.019	0.003
60	3.996	1.9999	1.0004	12.033	6.020	0.003
100	3.9956	1.9997	1.00038	12.032	6.019	0.003
200	3.9939	1.9989	0.99999	12.028	6.016	0.000
500	3.987	1.9955	0.9983	12.013	6.001	-0.015
1000	3.9692	1.9866	0.9938	11.974	5.962	-0.054
2000	3.90103	1.9529	0.977	11.824	5.814	-0.202
2500	3.8444	1.92501	0.963	11.697	5.689	-0.327
3000	3.767	1.8872	0.94418	11.520	5.516	-0.499
4000	3.5347	1.7747	0.88805	10.967	4.982	-1.031
5000	3.1744	1.6081	0.8047	10.033	4.126	-1.887
6000	2.7288	1.3948	0.6981	8.719	2.890	-3.122
6500	2.499	1.2778	0.6396	7.955	2.129	-3.882
7000	2.2705	1.1587	0.5801	7.122	1.279	-4.730
8000	1.83	0.9296	0.4649	5.249	-0.634	-6.653
10000	1.1055	0.5594	0.2799	0.871	-5.046	-11.060
15000	0.3024	0.15366	0.077066	-10.388	-16.269	-22.263
20000	0.10044	0.0516	0.025946	-19.962	-25.747	-31.719
50000	0.00265	0.0013	0.00084	-51.535	-57.694	-61.514

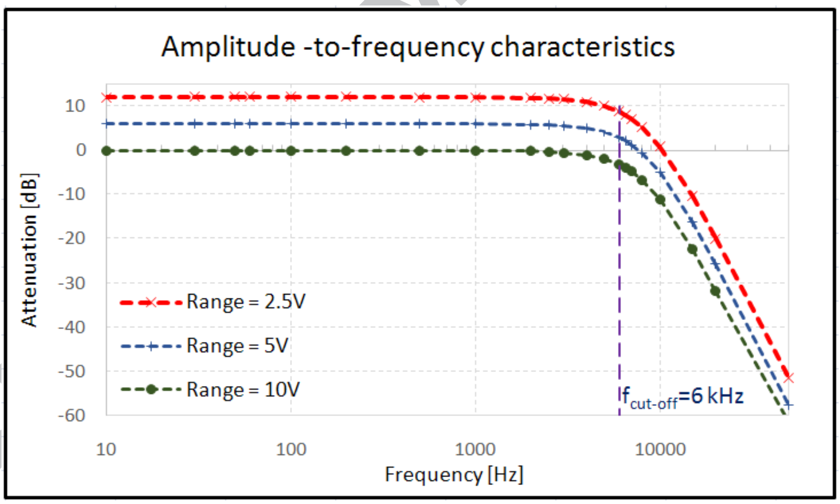

Figure 9. Preamplifier amplitude-to-frequency characteristics for input voltage ranges 2.5V, 5V and 10V

IV. Calculation of Measurement Uncertainty

Final segment in metrological assessment of the realized computer-based PQ signal generator is calculation of measurement uncertainty components and presentation of measurement uncertainty budget. Measurement uncertainty calculation is performed according to the recommendations of standard Guide to the Expression of Uncertainty in Measurement [15], defined by International Organization for Standardization – ISO. Entire procedure includes two basic segments: calculation of signal amplifier uncertainty and calculation of DAQ card uncertainty components. Both segments are divided in two parts: calculation of Root Mean Square (RMS) voltage uncertainty and calculation of frequency uncertainty, which is described and presented in the following section.

A. Amplifier voltage uncertainty

Measurement system for calculation of amplifier voltage uncertainty is consisting of the reference calibrator Fluke 5500A [21] for generation of amplifier input voltage signals, and 6 ½ digital multimeter Fluke 8846A [22] for measurement of amplifier output RMS voltage values. Warm-up time for both instruments was 1 hour. Reference calibrator Fluke 5500A is set to constant voltage value of 2.902 V (for the amplifier range of ± 5 V), which corresponds to the nominal amplifier output voltage value of 230 V. Measurements of amplifier output voltage values are performed for two different values of signal frequency, 50 Hz and 1 kHz. In order to calculate the Type A measurement uncertainty, 10 measurement cycles for each input signal frequency value were performed. Time interval between two successive measurement cycles is set to 5 min. Measured amplifier output RMS voltage values and calculated standard deviations, for two signal frequency values, 50 Hz and 1 kHz, are presented in Table III. Overall measurement uncertainty budget, including calculations of standard, combined and expanded amplifier voltage uncertainty, is presented in Table IV.

TABLE III

MEASUREMENT RESULTS AND CALCULATED STANDARD DEVIATIONS – AMPLIFIER RMS VOLTAGE VALUES (FOR 50 HZ AND 1 KHZ FREQUENCY)

	50 Hz	1 kHz
Ord. no. of measurements	V_{rms} [V]	V_{rms} [V]
1	230.056	229.877
2	230.065	229.877
3	230.072	229.871
4	230.068	229.872
5	230.063	229.869
6	230.051	229.872
7	230.062	229.869
8	230.068	229.868
9	230.071	229.866
10	230.059	229.869
ST. DEV	0.00638	0.00346
ST. DEV/ $\sqrt{n}$	0.00202	0.00110
$V_{average}$ (V)	230.064	229.871

TABLE IV

OVERALL MEASUREMENT UNCERTAINTY BUDGET – STANDARD, COMBINED AND EXPANDED AMPLIFIER VOLTAGE UNCERTAINTY CALCULATIONS

Source	Type	Notation	Uncertainty value 50Hz [V]	Uncertainty value 1 kHz [V]	Sensitivity coefficients	Probability distribution	Coverage factor	Standard uncertainty 50 Hz [V]	Standard uncertainty 1 kHz [V]	Degrees of freedom
Standard deviation (repeatability)	A	u_A	0,0020162	0,0010954	1	Normal	1	0,0020162	0,0010954	9
Calibrator uncertainty	B	u_{B1}	0,06907905	0,0690213	1	Normal	2,58	0,026774826	0,026752442	inf
Calibrator resolution	B	u_{B2}	0,00001	0,00001	1	Uniform	1,732050808	5,7735E-06	5,7735E-06	inf
Multimeter uncertainty	B	u_{B3}	0,3630381	0,3629226	1	Normal	2,58	0,140712442	0,140667674	inf
Multimeter resolution	B	u_{B4}	0,0005	0,0005	1	Uniform	1,732050808	0,000288675	0,000288675	inf
							Combined	0,14325	0,14319	
							Expanded k=1.96	0,28077	0,28066	

Calculation of standard measurement uncertainty involves Type A uncertainty (standard deviation of the mean) and Type B uncertainty (calibrator uncertainty, calibrator resolution, multimeter uncertainty and multimeter resolution). Standard deviation of the mean (Type A uncertainty) is calculated according to statistical methods applied on measurement results, using the equation:

$$u_A(V) = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}\left(V_{rms} - V_{average}\right)^2} \tag{6}$$

Type B measurement uncertainties (calibrator uncertainty and resolution, multimeter uncertainty and resolution) are calculated according to data and accuracies provided by specifications of applied instruments calibrator Fluke 5500A and digital multimeter Fluke 8846A. According to instrument specifications [21], the calibrator absolute uncertainty is defined as $\Delta V_{cal} = \pm$ (0.03 % of output + 60 μV). Hence, having in mind the calibrator resolution $V_{cal\text{-}res}$ = 10 μV, the corresponding calibrator Type B uncertainty (u_{Bcal}) is calculated by:

$$u_{Bcal}{}^2(V) = u^2{}_{B1} + u^2{}_{B2} = \left(\frac{\Delta V_{cal}}{2.58}\right)^2 + \left(\frac{1}{2}\frac{V_{cal-res}}{\sqrt{3}}\right)^2 \tag{7}$$

Similarly, the multimeter voltage uncertainty (u_{Bmul}) is calculated according the instrument specifications [22], $\Delta V_{mul} = \pm$ (0.06 % of output + 0.0225 % of range). The multimeter resolution is $V_{mul\text{-}res}$ = 1 mV. The corresponding multimeter Type B uncertainty (u_{Bmul}) is:

$$u_{Bmul}{}^2(V) = u^2{}_{B3} + u^2{}_{B4} = \left(\frac{\Delta V_{mul}}{2.58}\right)^2 + \left(\frac{1}{2}\frac{V_{mul-res}}{\sqrt{3}}\right)^2 \tag{8}$$

Calculation of the combined amplifier voltage measurement uncertainty ($u_{CAMP\text{-}V}$) is based on the previously calculated individual Type A and Type B uncertainties, using the following equation [15]:

$$u_{CAMP-V}(V) = \sqrt{u_A^2 + u_{Bcal}^2 + u_{Bmul}^2} \tag{9}$$

Finally, expanded measurement uncertainty ($u_{EXP\text{-}V}$) is calculated for desired confidence probability level of 95% (value of coverage factor *k* is 1.96). Using the previously calculated value of combined uncertainty, expanded measurement uncertainty is:

$$u_{EXP-V}(V) = k u_{CAMP-V}(V) = 1.96 u_{CAMP-V}(V) \tag{10}$$

The results reported in Table IV suggest that expanded amplifier voltage measurement uncertainties are: ± 0.28077 V and ± 0.28066 V for frequency of 50 Hz and 1 kHz, respectively.

B. Amplifier frequency uncertainty

The procedure for calculation of amplifier frequency uncertainty includes the reference calibrator Fluke 5500A [21] for generation of amplifier input signals with various frequencies, and 6 ½ digital multimeter Fluke 8846A [22] for measurement of amplifier output frequencies. Reference calibrator Fluke 5500A is set to generate voltage signals with various frequencies of 50 Hz, 1 kHz and 2.5 kHz. Measured amplifier output frequencies and calculated standard deviations in 10 measurement cycles, for three signal frequencies, 50 Hz, 1 kHz and 2.5 kHz, are presented in Table V. Overall measurement uncertainty budget, including calculations of standard, combined and expanded amplifier frequency uncertainty components, is presented in Table VI.

TABLE V

MEASUREMENT RESULTS AND CALCULATED STANDARD DEVIATIONS – AMPLIFIER FREQUENCY VALUES (FOR 50 HZ, 1 KHZ AND 2.5 KHZ)

	50 Hz	1 kHz	2.5 kHz
Ord. no. of measurements	f [Hz]	f [Hz]	f [Hz]
1	50.0006	1000.006	2500.02
2	50.0007	1000.007	2500.02
3	50.0007	1000.007	2500.02
4	50.0006	1000.006	2500.01
5	50.0008	1000.007	2500.02
6	50.0005	1000.006	2500.02
7	50.0007	1000.006	2500.02
8	50.0006	1000.007	2500.01
9	50.0005	1000.006	2500.02
10	50.0008	1000.007	2500.02
ST. DEV	0.00010	0.00050	0.00400
ST. DEV/ $\sqrt{n}$	0.00003	0.00016	0.00126
$f_{average}$ (Hz)	50.00065	1000.0065	2500.018

TABLE VI

OVERALL MEASUREMENT UNCERTAINTY BUDGET – STANDARD, COMBINED AND EXPANDED AMPLIFIER FREQUENCY UNCERTAINTY CALCULATIONS

Source	Type	Notation	Uncertainty value 50 Hz [Hz]	Uncertainty value 1 kHz [Hz]	Uncertainty value 2.5 kHz [Hz]	Sensitivity coefficients	Probability distribution	Coverage factor	Standard uncertainty 50 Hz [Hz]	Standard uncertainty 1 kHz [Hz]	Standard uncertainty 2.5 kHz [Hz]	Degrees of freedom
Standard deviation (repeatability)	A	u_A	0,0000324	0,0001581	0,0012649	1	Normal	1	0,0000324	0,0001581	0,0012649	9
Calibrator uncertainty	B	u_{B1}	0,002250016	0,026000163	0,06350045	1	Normal	2,58	0,000872099	0,010077582	0,024612578	inf
Calibrator resolution	B	u_{B2}	0,005	0,05	0,5	1	Uniform	1,732050808	0,002886751	0,028867513	0,288675135	inf
Multimeter uncertainty	B	u_{B3}	0,005000065	0,10000065	0,2500018	1	Normal	2,58	0,00193801	0,038759942	0,096899922	inf
Multimeter resolution	B	u_{B4}	0,00005	0,0005	0,005	1	Uniform	1,732050808	2,88675E-05	0,000288675	0,002886751	inf
								Combined	0,00358	0,04937	0,30551	
								Expanded k=2	0,00703	0,09676	0,59881	

Calculation of standard frequency uncertainty involves Type A uncertainty (standard deviation of the mean) and Type B uncertainty (calibrator uncertainty, calibrator resolution, multimeter uncertainty and multimeter resolution). Standard deviation of the mean (Type A frequency uncertainty) is calculated according to statistical methods applied on measurement results, using the equation:

$$u_A(Hz) = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}\left(f_i - f_{average}\right)^2} \tag{11}$$

Type B frequency uncertainties (calibrator uncertainty and resolution, multimeter uncertainty and resolution) are calculated according to data and accuracies provided by specifications of applied instruments calibrator Fluke 5500A and digital multimeter Fluke 8846A. According to instrument specifications [21], calibrator absolute frequency uncertainty is $\Delta f_{cal} = \pm$ (25 ppm of output + 1 mHz). The calibrator resolution ($f_{cal\text{-}res}$) is 0.01 Hz, 0.1 Hz and 1 Hz for 50 Hz, 1 kHz and 2.5 kHz, respectively. Hence, the corresponding calibrator Type B uncertainty (u_{Bcal}) is calculated by:

$$u_{Bcal}{}^2(Hz) = u^2{}_{B1} + u^2{}_{B2} = \left(\frac{\Delta f_{cal}}{2.58}\right)^2 + \left(\frac{1}{2}\frac{f_{cal-res}}{\sqrt{3}}\right)^2$$

(12)

Similarly, the multimeter absolute frequency uncertainty (u_{Bmul}) is $\Delta f_{mul} = \pm$ (0.01 % of output), whereas the resolution ($f_{mul\text{-}res}$) is 0.1 mHz, 1 mHz, and 10 mHz for 50 Hz, 1 kHz and 2.5 kHz, respectively. The multimeter Type B measurement uncertainty is:

$$u_{Bmul}{}^2(Hz) = u^2{}_{B3} + u^2{}_{B4} = \left(\frac{\Delta f_{mul}}{2.58}\right)^2 + \left(\frac{1}{2}\frac{f_{mul-res}}{\sqrt{3}}\right)^2 \quad (13)$$

Calculations of combined uncertainty for frequency measurement (u_{CAMP-f}) and the expanded measurement uncertainty (u_{EXP-f}) are performed similarly like (9) and (10). From Table VI it can be seen that the expanded amplifier frequency uncertainties are: ± 7.03 mHz, ± 96.76 mHz and ± 598.81 mHz for frequencies of 50 Hz, 1 kHz and 2.5 kHz, respectively.

C. DAQ card voltage uncertainty

Measurement system for calculation of DAQ card voltage uncertainty involves computer with DAQ card PCIe NI 6343 [23] for generation of reference voltage signals, and 6 ½ digital multimeter Fluke 8846A [22] for measurement of DAQ card output RMS voltage. Nominal RMS voltage value of the analog signals generated by DAQ card was set to 5V. Measurement of DAQ card output voltage is performed in 10 cycles, in the output range of 10V. Measured DAQ card output RMS voltage and calculated standard deviations, for two signal frequencies, 50 Hz and 1 kHz, are presented in Table VII. Measurement uncertainty budget, including calculations of standard, combined and expanded DAQ card voltage uncertainties, is presented in Table VIII.

TABLE VII

MEASUREMENT RESULTS AND CALCULATED STANDARD DEVIATIONS – DAQ CARD RMS VOLTAGE VALUES (FOR 50 HZ AND 1 KHZ FREQUENCY)

	50 Hz	1 kHz
Ord. no. of measurements	Vrms [V]	Vrms [V]
1	4.99308	4.99381
2	4.99298	4.99378
3	4.99318	4.99379
4	4.99311	4.99378
5	4.99305	4.99376
6	4.99318	4.99376
7	4.993	4.99381
8	4.99309	4.99378
9	4.99297	4.99376
10	4.99315	4.99376
ST. DEV	0.00007	0.00002
ST. DEV/$\sqrt{n}$	0.00002	0.00001
$V_{average}$ (V)	4.993079	4.993779

TABLE VIII

OVERALL MEASUREMENT UNCERTAINTY BUDGET – STANDARD, COMBINED AND EXPANDED DAQ CARD VOLTAGE UNCERTAINTY CALCULATIONS

Source	Type	Notation	Uncertainty value 50Hz [V]	Uncertainty value 1 kHz [V]	Sensitivity coefficients	Probability distribution	Coverage factor	Standard uncertainty 50 Hz [V]	Standard uncertainty 1 kHz [V]	Degrees of freedom
Standard deviation (repeatability)	A	u_A	0,0000235	0,0000059	1	Normal	1	0,0000235	0,0000059	9
Multimeter uncertainty	B	u_{B1}	0,005995847	0,005996267	1	Normal	2,58	0,002323972	0,002324135	inf
Multimeter resolution	B	u_{B2}	5,00E-06	5,00E-06	1	Uniform	1,732050808	2,88675E-06	2,88675E-06	inf
DAQ Card uncertainty	B	u_{B3}	3,27E-06	3,27E-06	1	Normal	2,58	1,26783E-06	1,26783E-06	inf
DAQ card resolution	B	u_{B4}	0,000152588	0,000152588	1	Uniform	1,732050808	8,80967E-05	8,80967E-05	inf
							Combined	0,00233	0,00233	
							Expanded k=2	0,00456	0,00456	

The DAQ card Type A voltage measurement uncertainty is calculated by (6). According to [22], the multimeter absolute voltage uncertainty is $\Delta V_{mul} = \pm$ (0.06 % of output + 0.03 % of range). The multimeter voltage resolution is $V_{mul-res}$ = 10 µV. Hence, the corresponding multimeter Type B uncertainty (u_{Bmul}) is given with:

$$u_{Bmul}^{2}(V) = u^{2}_{B1} + u^{2}_{B2} = \left(\frac{\Delta V_{mul}}{2.58}\right)^{2} + \left(\frac{1}{2}\frac{V_{mul-res}}{\sqrt{3}}\right)^{2}$$

(14)

Having in mind the DAQ card PCIe NI 6343 specifications [23], the DAQ card voltage absolute uncertainty at full scale is ΔV_{DAQ} = 3.271 μV. The DAQ card voltage resolution is $\Delta V_{DAQ\text{-}res}$ = 305 μV. Hence, the corresponding DAQ card Type B uncertainty (u_{BDAQ}) is calculated as:

$$u_{BDAQ}^{2}(V) = u^{2}_{B3} + u^{2}_{B4} = \left(\frac{\Delta V_{DAQ}}{2.58}\right)^{2} + \left(\frac{1}{2}\frac{V_{DAQ-res}}{\sqrt{3}}\right)^{2} \quad (15)$$

The combined voltage measurement uncertainty ($u_{CDAQ\text{-}V}$) is calculated by using (14) and (15) with:

$$u_{CDAQ-V}(V) = \sqrt{u_{A}^{2} + u_{Bmul}^{2} + u_{BDAQ}^{2}} \quad (16)$$

D. *DAQ card frequency uncertainty*

Procedure for calculation of DAQ card frequency uncertainty includes computer with data acquisition card NI 6343 [23] for generation of reference signals with various frequency values, and 6 ½ digital multimeter Fluke 8846A [22] for measurement of DAQ card output frequency. Measured DAQ card output frequencies and calculated standard deviations in 10 measurement cycles, for three signal frequencies, 50 Hz, 1 kHz and 2.5 kHz, are presented in Table IX. Overall uncertainty budget for frequency measurement, including calculations of standard, combined and expanded DAQ card frequency uncertainty, is presented in Table X.

TABLE IX
MEASUREMENT RESULTS AND CALCULATED STANDARD DEVIATIONS – DAQ CARD FREQUENCY VALUES (FOR 50 HZ, 1 KHZ AND 2.5 KHZ)

	50 Hz	1 kHz	2.5 kHz
Ord. no. of measurements	f [Hz]	f [Hz]	f [Hz]
1	50.0503	1000.993	2502.48
2	50.0499	1000.991	2502.48
3	50.0494	1000.993	2502.49
4	50.0490	1000.994	2502.48
5	50.0499	1000.992	2502.48
6	50.0497	1000.991	2502.49
7	50.0495	1000.992	2502.48
8	50.0503	1000.994	2502.49
9	50.0492	1000.993	2502.48
10	50.0486	1000.994	2502.48
ST. DEV	0.00052	0.00110	0.00458
ST. DEV/ $\sqrt{n}$	0.00017	0.00035	0.00145
$f_{average}$ (Hz)	50.04958	1000.9927	2502.483

TABLE X

OVERALL MEASUREMENT UNCERTAINTY BUDGET – STANDARD, COMBINED AND EXPANDED DAQ CARD FREQUENCY UNCERTAINTY CALCULATIONS

Source	Type	Notation	Uncertainty value 50Hz [Hz]	Uncertainty value 1 kHz [Hz]	Uncertainty value 2.5 kHz [Hz]	Sensitivity coefficients	Probability distribution	Coverage factor	Standard uncertainty 50 Hz [Hz]	Standard uncertainty 1 kHz [Hz]	Standard uncertainty 2.5 kHz [Hz]	Degrees of freedom
Standard deviation (repeatability)	A	u_A	0,0001654	0,0003479	0,0014491	1	Normal	1	0,0001654	0,0003479	0,0014491	9
Multimeter uncertainty	B	u_{B1}	0,005004958	0,10009927	0,2502483	1	Normal	2,58	0,001939906	0,038798167	0,096995465	inf
Multimeter resolution	B	u_{B2}	0,00005	0,0005	0,005	1	Uniform	1,732050808	2,88675E-05	0,000288675	0,002886751	inf
DAQ Card uncertainty	B	u_{B3}	1,385E-07	0,0000555	0,000345	1	Normal	2,58	5,36822E-08	2,15116E-05	0,000133721	inf
DAQ card resolution	B	u_{B4}	0,0000125	0,005	0,03125	1	Uniform	1,732050808	7,21688E-06	0,002886751	0,018042196	inf
								Combined	0,00195	0,03891	0,09871	
								Expanded k=2	0,00382	0,07626	0,19348	

The DAQ card Type A and Type B frequency measurement uncertainty (u_{Bmul}) are calculated by (11) and (13), respectively.

DAQ card uncertainty for frequency measurement (u_{B3}) is calculated on the basis of data provided by acquisition card PCIe NI 6343 specifications (timing accuracy 50 ppm of sample rate) when considering maximum sample rate of 900 kS/s. DAQ card resolution for frequency measurement (u_{B4}) is calculated using the specified nominal value for DAQ card timing resolution of 10 ns [23]. The overall Type B DAQ card frequency uncertainty is:

$$u_{BDAQ-f}{}^2(Hz) = u^2{}_{B3} + u^2{}_{B4}$$

(17)

The combined DAQ card frequency uncertainty (u_{CDAQ-f}) is given based on the previously calculated individual type A and type B frequency measurement uncertainty values, using the following square root equation:

$$u_{CDAQ-f}(Hz) = \sqrt{u_A^2 + u_{Bmul}^2 + u_{BDAQ-f}^2} \quad (18)$$

E. Computer-based PQ signal generator uncertainty

When calculating the overall computer-based PQ signal generator expanded uncertainty, one have to take into account booth DAQ card and amplifier uncertainties. In such case, for confidence probability level of 95% (value of coverage factor *k* is 1.96) the expanded voltage uncertainty is:

$$u_{EXPPQ-V}(V) = 1.96\sqrt{u_{CAMP-V}^2 + u_{CDAQ-V}^2}$$

(19)

Considering the values reported in Table IV and Table VIII, according to (19), the expanded computer-based PQ signal generator voltage uncertainty for the nominal power line voltage level of 230 V and frequency of 50 Hz is: 230 V ± 0.28 V.

On the other hand, the expanded frequency uncertainty is:

$$u_{EXPPQ-f}(Hz) = 1.96\sqrt{u_{CAMP-f}^2 + u_{CDAQ-f}^2}$$

(20)

Therefore, according to the values reported in Table VI and Table X, according to (20), the expanded frequency uncertainty for the nominal power line voltage level of 230 V and frequency of 50 Hz is: 50 Hz ± 8 mHz.

F. Comparison between the commercial and the realized PQ signal generator

To support the evaluated technical and metrological performances of the realized PQ signal generator, a detailed comparison with several commercial generators has been performed. Three PQ signal generators with different performances and technical capabilities were selected: Keysight-6811B [24], Calmet C300 [25] and Metrel MI2191 [26]. The instruments Keysight-6811B and Calmet C300 are high precision PQ generators intended for calibration and precision measurements, whereas Metrel MI2191 is low-accuracy instrument for testing purposes. The technical data summary of the PQ generators is given in Table

XI.

TABLE XI

TECHNICAL DATA SUMMARY OF DIFFERENT COMMERCIAL POWER QUALITY GENERATORS AND THE PC-BASED SIGNAL GENERATOR

Perameters	Keysight-6811B	Calmet C300	Metrel MI2191	PC-based PQ generator
Maximum RMS voltage	300 V	560 V	285 V	280 V
Maximum RMS current	3.25 A	120 A	11 mA	17.8 mA
Maximum apparent power	375 VA	67.2 kVA	3 VA	5 VA
Frequency range	DC + 45 Hz to 1 kHz	DC to 3.2 kHz	no information	DC to 2.5 kHz
Output impedance	Programmable 0 to 1 Ω	no information	1.8 kΩ	100 Ω / without short cirtcuit protection
Output voltage resolution	10 mV	1 mV	1.11 V	4.27 mV
Voltage uncertainty (230 V, 50 Hz)	± 0,645 V	± 0.046 V	± 21.5 V	± 0.28 V
Frequency uncertainty (50 Hz)	± 5 mHz	± 2.5 mHz	no information	± 8 mHz
Short circuit protection	YES	YES	YES	YES
Number of phases	Single	Three	Single	Single/possible three phase upgrade
PQ disturbances	All according EN50160 and EN 61000-4 standard series	All according EN50160 and EN 61000-4 standard series	All according EN 61010-1	All according EN50160 and EN 61000-4 standard series
Hardware functionality	Stand alone with PC support	PC-based	Stand alone with PC support	PC-based
Software functionality	Dedicated software with closed architecture	Dedicated software with closed architecture	RS232 communication interface support	LabVIEW-based with open architecture
Portability	Limited portability	Stationarry	Portable	Portable
Test signals recording	Yes	Yes	No	Yes

Regarding the maximal voltage, current and power, the instruments show different performances. Namely, Keysight-6811B and Calmet C300 can deliver significantly higher power comparing to the Metrel MI2191 and the realized PQ signal generator. This can be important in cases where high-power loads are tested and the influence of PQ disturbances needs to be evaluated. On the other hand, even the lowest maximal power of 3 VA (in the case of Metrel MI2191) is sufficient for testing of any PQ measurement instrument. All instruments cover the PQ disturbance voltage range for the low-voltage power distribution networks.

In general, the developed PC-based signal generator covers the frequency range of the commercial PQ generators, except in the case of Calmet C300 where signals up to 3.2 kHz can be generated. The frequency range is usually determined according international standards, such as: EN50160, EN 61000-4 series, etc.

As expected, the PQ Calibrator Calmet C300 has lowest voltage and frequency uncertainty. However, the developed PQ signal generator uncertainty is comparable to the uncertainty of Keysight-6811B and much better than the Metrel MI2191. Therefore, it is clear that the generator can be successfully used for measurement and testing purposes. Moreover, its uncertainty can be further improved by using a higher quality DAQ card.

Due to the closed functional architecture developed according to the specific quality standards, for example EN50160, the commercial instruments are not fully flexible and hardly adaptable to meet some specific user demands and requirements. Therefore, the hardware and software functionality are considered as one of the major advantages of the proposed solution. The hardware and software architecture of the PQ generator ensures easy upgrade to three phase solution, as well as simple implementation of new functional features. This is especially important when the generator is intended to be used for research purposes.

V. CONCLUSION

In this paper, implementation of computer-based electrical power quality signal generator was proposed. The generator consists of virtual instrument for PQ disturbance simulation and power amplifier for scaling the signals to the power line voltage level. Several examples of characteristic PQ disturbances were reproduced with the generator and were recorded by commercial PQ instrument. Afterwards, the paper is focused on design and implementation concepts for PQ signal amplifier, including preamplifier, limiter, low pass antialiasing filter and power amplifier. The metrological performances of the realized

PQ amplifier were evaluated with professional instrumentation and satisfactory results were achieved. For final metrological assessment of realized PQ signal generator, procedure for measurement uncertainty calculation is performed, according to the recommendations of document Guide to the Expression of Uncertainty in Measurement, defined by International Organization for Standardization – ISO. This procedure includes calculation of standard, combined and expanded measurement uncertainty components and presentation of overall measurement uncertainty budget. Uncertainty calculation is based on three main segments: calculation of signal amplifier uncertainty, DAQ card uncertainty, and computer-based PQ generator uncertainty. The experimental tests show that, by following the design concepts reported in this paper, computer-based PQ generator voltage uncertainty of ± 0.28 V and frequency uncertainty of ± 8 mHz can be achieved.
In the paper comparison between several commercial PQ generators regarding the most important technical parameters have been performed, where pros and cons were identified. Having in mind the evaluated technical summary, and the simplicity of the realized PQ signal generator, authors think that such performances can be considered as satisfactory.

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Highlights

- Realization of virtual instrument for simulation of power quality (PQ) disturbances
- Implementation of PQ signal amplifier (230 V), including preamplifier, low pass antialiasing filter and power amplifier
- The signal generator can be used as a source of reference signals for testing instruments for measurement of quality parameters, including various algorithms for PQ disturbance detection
- The metrological performances (measurement uncertainty calculation) of the PQ signal generator were evaluated with professional instrumentation and satisfactory results were achieved
- This computer-based signal generator can be used as suitable and cost effective alternative to the instruments for testing the PQ meters and analyzers