# EVALUATING THE UNCERTAINTY OF A VIRTUAL POWER QUALITY DISTURBANCE GENERATOR

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**Abstract:**
This paper presents the metrological evaluation of a proposed virtual power quality (PQ) disturbance generator. The calibration and measurement uncertainty estimation procedures for the RMS voltage and frequency of the generator are explained in detail and the obtained results are presented and discussed. The results show that the measurement uncertainty of the PQ disturbance generator for all reference points is satisfactory, making it suitable for generation of PQ signals for research purposes, especially in the development, testing and improvement of PQ event classifiers.

**Keywords:** power quality; measurement uncertainty; calibration; signal generator; virtual instrumentation

## 1. INTRODUCTION

Due to intensive use of non-linear loads, problems defined under power quality (PQ) arise in modern electrical grids. In Europe, the voltage characteristics of the public power distribution system for normal operation are defined with the European standard on power quality: EN 50160 [1]. To address these problems, real-time monitoring and PQ disturbance classification systems are needed at numerous locations in the power grid. Fault detection based on data analytics with advanced metering infrastructure are essential for the security of power systems [2]. Systems for power quality monitoring are already implemented in some power grids. They are mostly based on measurement devices which only save raw voltage signals [3]-[5]. Other monitoring systems perform real-time processing and provide PQ indicators [6]-[7]. However, industrial grade instrumentation specifically designed for PQ monitoring is relatively expensive, hence the focus in recent years on development of virtual instrumentation-based PQ monitoring systems [8]-[9], as well as algorithms for fast and accurate detection and classification of PQ disturbances, such as the ones presented in [10]-[11]. Using such algorithms combined with virtual instrumentation can provide more flexible, cost-effective and decentralized solutions. However, the development of these algorithms requires a large amount of curated PQ disturbance data, which can be hard to obtain. There is a lack of publicly accessible good quality datasets of this kind [12]. Although there are commercially available PQ disturbance generators on the market which can be used to obtain this kind of data, they are too expensive for research purposes. Consequently, virtual instrumentation-based generators of PQ disturbances have been developed [13]-[14], which can be used to obtain PQ data for research purposes.

This paper will focus on the metrological evaluation of the virtual PQ disturbance generator proposed in [14], in order to determine its usability in research purposes, especially for testing, optimization and improvement of PQ disturbance classifiers.

## 2. VIRTUAL POWER QUALITY DISTURBANCE GENERATOR

The main purpose of the designed virtual power quality disturbance generator, which is the subject of the metrological evaluation presented in this paper, is to generate and reproduce reference voltage signals and simulate standard voltage quality disturbances in accordance with the European standard EN50160 [1].

The generator mainly consists of two functional segments: a software application running on a personal computer and hardware components. The software application is developed in the LabVIEW graphical programming environment. The software realization of the virtual PQ generator, its functionalities, capabilities and modes of operation are fully presented in [14]. The hardware components of the generator include a data acquisition (DAQ) device and a power quality signal amplifier. The DAQ device is used for hardware reproduction of the voltage waveforms generated by the software application. The data acquisition device used is a NI USB-6218 multifunction acquisition device. The PQ signal amplifier is used to amplify the output voltage signal from the DAQ device to a nominal voltage level of 230 V. A detailed description of the design, functionality and characteristics of the PQ signal amplifier is given in [15].

A schematic representation of the PQ disturbance generator and its consisting hardware and software components is given in Figure 1.

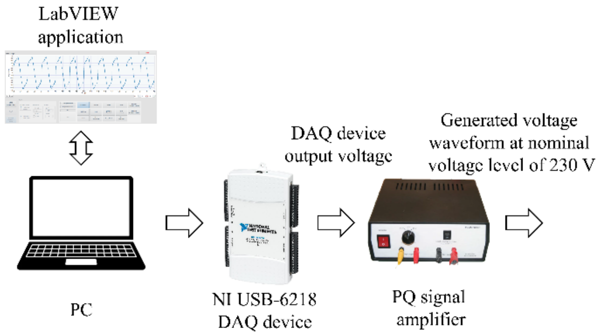


Figure 1: A schematic representation of the virtual PQ disturbance generator and its components

## 3. CALIBRATION AND MEASUREMENT UNCERTAINTY ESTIMATION

In order to perform a metrological assessment of the realized PQ generator, a calibration and measurement uncertainty estimation was carried out. The calibration and measurement uncertainty calculation procedures, as well as the measurement uncertainty budget are presented in the following section.

The measurement uncertainty estimation is performed according to the recommendations in the Guide to the Expression of Uncertainty in Measurement [16], defined by the International Organization for Standardization – ISO. The procedure is divided into two segments: estimation of RMS voltage uncertainty and estimation of frequency uncertainty. Another approach to estimating the measurement uncertainty would be by using the Monte Carlo Method [17]. Nevertheless, the authors believe that this method would yield similar results, and hence opted for the GUM approach.

### 3.1. Voltage Uncertainty

The measurement setup for RMS voltage calibration of the PQ disturbance generator consists of NI USB-6218 DAQ device used to generate the input voltage signals for the amplifier and a 6½-digit digital multimeter Fluke 8846A for measurement of the amplifier output RMS voltage values. The experimental system including the PQ disturbance generator, NI USB-6218 DAQ device and the Fluke 8846A reference multimeter is shown in Figure 2. The components of the measurement uncertainty budget for the RMS voltage of the generator are presented in Table 1. The PQ amplifier was calibrated using a FLUKE 5500A calibrator prior to the measurements, therefore its drift is not included in the uncertainty budget.

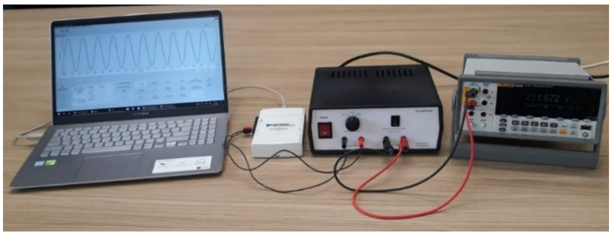

Figure 2: Experimental system used for calibration of the virtual PQ disturbance generator

For calibration of the RMS voltage, six measurement points for the output of the PQ amplifier are taken: 230 V, 253 V, 207 V, 110 V, 121 V and 99 V. The warm-up time for the instruments is 1 h. The amplifier is set to the ±5 V input voltage range. Its amplification at this range is $A$ = 79.554. The output of the DAQ device is set to a constant RMS value corresponding to the aforementioned measurement points (2.891 V, 3.18 V, 2.602 V, 1.383 V, 1.521 V and 1.244 V respectfully). The frequency of the generated voltage signal is 50 Hz and the signal is generated at a sampling rate of 25 kS/s. For each measurement point, 10 measurements are taken at five-minute time intervals between two successive measurements. The average measured voltage RMS values, as well as the calculated standard deviations for each measurement point are presented in Table 2.

The calculation of the standard measurement uncertainty of the output RMS voltage of the PQ disturbance generator includes Type A uncertainty (standard deviation of the mean) and Type B uncertainty (DAQ device accuracy, DAQ device resolution, multimeter uncertainty and multimeter resolution). The standard deviation of the mean is calculated according to statistical methods applied on the measurement results, using the equation:

$$u_A = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}\left(V_i - V_{avg}\right)^2}\,. \tag{1}$$

Type B measurement uncertainties are calculated according to data and accuracies provided by the specifications of the applied instruments: digital multimeter Fluke 8846A [18] and DAQ device NI USB-6218 [19].

According to instrument specifications, the multimeter absolute uncertainty for the AC voltage range of 1000 V and frequency range from 10 Hz – 20 kHz is defined as $\Delta V_{DMM}$ = ± (0.06 % of measurement + 0.03 % of range). The multimeter resolution for the same range is $\Delta V_{DMM\text{-}res}$ = 10 mV, therefore the corresponding DMM Type B uncertainty $u_{B\text{-}DDM}$ is calculated by:

Table 1: Measurement uncertainty budget – RMS voltage

| Source | Type | Notation | Sensitivity coefficients | Probability distribution | Divisor | Degrees of freedom |
|---|---|---|---|---|---|---|
| Standard deviation (repeatability) | A | $u_A$ | 1 | Normal | 1 | 9 |
| DMM accuracy | B | $u_{B1}$ | 1 | Uniform | 1/√3 | ∞ |
| DMM resolution | B | $u_{B2}$ | 1 | Uniform | 1/√3 | ∞ |
| DAQ accuracy | B | $u_{B3}$ | 79.554 | Uniform | 1/√3 | ∞ |
| DAQ resolution | B | $u_{B4}$ | 79.554 | Uniform | 1/√3 | ∞ |

Table 2: Measurement results and calculated standard deviation (ST. DEV) – RMS voltage values

| | 230 V $V_{RMS}$ [V] | 253 V $V_{RMS}$ [V] | 207 V $V_{RMS}$ [V] | 110 V $V_{RMS}$ [V] | 121 V $V_{RMS}$ [V] | 99 V $V_{RMS}$ [V] |
|---|---|---|---|---|---|---|
| $V_{avg}$ [V] ($n$ = 10) | 229.4747 | 252.8879 | 207.4483 | 110.3206 | 121.4759 | 99.3593 |
| ST. DEV | 0.0698 | 0.0519 | 0.0417 | 0.0077 | 0.0437 | 0.0091 |
| ST. DEV / $\sqrt{n}$ | 0.0221 | 0.0164 | 0.0132 | 0.0024 | 0.0138 | 0.0029 |

$$u_{B-DMM}^2 = u_{B1}^2 + u_{B2}^2 \ . \tag{2}$$

$$u_{B-DMM}^2 = \left(\frac{\Delta V_{DMM}}{\sqrt{3}}\right)^2 + \left(\frac{1}{2}\frac{V_{DMM-res}}{\sqrt{3}}\right)^2 \ . \tag{3}$$

The output voltage signal of the PQ generator $V_{out}$ is obtained by amplifying the voltage signal generated by the DAQ device $V_{DAQ}$ and is calculated using equation (4). The amplifier's amplification $A$, for the ±5 V amplifier range is $A$ = 79.554.

$$V_{out} = A \cdot V_{DAQ} \ . \tag{4}$$

The sensitivity coefficients for the Type B uncertainties of the DAQ device, $c_3$ and $c_4$, can be calculated using the following equation:

$$\frac{\partial V_{out}}{\partial V_{DAQ}} = A = c_3 = c_4 \ . \tag{5}$$

Hence, the sensitivity coefficients $c_3$ and $c_4$ are equal to the amplifier's amplification. The nominal value of the PQ amplifier's amplification is A = 80, meaning that at the DAQ device's standardized output level of 5V, the output RMS voltage from the amplifier would be equal to 400 V, which is necessary PQ applications.

The absolute accuracy (which includes uncertainty due to drift) of the NI USB-6218 DAQ device $V_{DAQ}$ is calculated using the method provided in the instrument specification, and the DAQ device resolution $V_{DAQ\text{-}res}$ is calculated according to the DAC resolution of the device, $n$ = 16 bits and its output voltage range $V_r$ = ±10 V = 20 V, as follows:

$$V_{DAQ-res} = \frac{V_r}{2^n - 1} \ . \tag{6}$$

The corresponding DAQ device Type B uncertainty $u_{B\text{-}DAQ}$ is calculated by using the following equation:

$$u_{B-DAQ}^2 = c_3^2 u_{B3}^2 + c_4^2 u_{B4}^2 \ . \tag{7}$$

$$u_{B-DAQ}^2 = A^2\left(\frac{\Delta V_{DAQ}}{\sqrt{3}}\right)^2 + A^2\left(\frac{1}{2}\frac{V_{DAQ-res}}{\sqrt{3}}\right)^2 \ . \tag{8}$$

The combined voltage measurement uncertainty $u_{\_C\text{-}V}$ is calculated using the previously calculated individual Type A and Type B uncertainties, as follows:

$$u_{c-V} = \sqrt{u_A^2 + u_{B-DMM}^2 + u_{B-DAQ}^2} \ . \tag{9}$$

The number of overall effective degrees of freedom $v_{eff}$ for the combined uncertainty is calculated using the Welch-Satterthwaite equation:

$$v_{eff} = \frac{u_c^4(y)}{\sum_{i=1}^{N} \frac{c_i^4 u_i^4(x_i)}{v_i}} \ . \tag{10}$$

The number of effective degrees of freedom for the combined uncertainty of all six measurement points is a large number and can be considered as infinity ($v_{eff} = \infty$).

The expanded measurement uncertainty of the PQ disturbance generator output RMS voltage $u_{exp\text{-}V}$ is calculated for a confidence interval of 95 %. The coverage factor that corresponds to this confidence interval and effective degrees of freedom $v_{eff} = \infty$, adjusted according to the Student's t-distribution table is $k$ = 1.96.

$$u_{exp-V} = k \cdot u_{c-V} = 1.96 \cdot u_{c-V} \ . \tag{11}$$

The standard uncertainty for each of the uncertainty components, as well as the combined and expanded uncertainty for each of the measurement points are presented in Table 3. The expanded uncertainty is presented graphically in Figure 3.

The largest contributing component of the voltage RMS measurement uncertainty of the PQ disturbance generator is the Type B uncertainty of

Table 3: Standard, combined and expanded measurement uncertainty calculations – RMS voltage

| Source | Standard uncertainty [V] | | | | | |
|---|---|---|---|---|---|---|
| | **230 V** | **253 V** | **207 V** | **110 V** | **121 V** | **99 V** |
| $u_A$ | $2.206\cdot10^{-2}$ | $1.640\cdot10^{-2}$ | $1.318\cdot10^{-2}$ | $2.423\cdot10^{-3}$ | $1.382\cdot10^{-2}$ | $2.868\cdot10^{-3}$ |
| $u_{B\text{-}DMM}$ | $2.527\cdot10^{-1}$ | $2.608\cdot10^{-1}$ | $2.451\cdot10^{-1}$ | $2.114\cdot10^{-1}$ | $2.153\cdot10^{-1}$ | $2.076\cdot10^{-1}$ |
| $u_{B\text{-}DAQ}$ | $9.134\cdot10^{-1}$ | $9.210\cdot10^{-1}$ | $9.064\cdot10^{-1}$ | $8.845\cdot10^{-1}$ | $8.863\cdot10^{-1}$ | $8.828\cdot10^{-1}$ |
| Combined uncertainty $u_{C\text{-}V}$ | $9.479\cdot10^{-1}$ | $9.574\cdot10^{-1}$ | $9.390\cdot10^{-1}$ | $9.094\cdot10^{-1}$ | $9.122\cdot10^{-1}$ | $9.069\cdot10^{-1}$ |
| Effective degrees of freedom $\nu_{eff}$ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| Coverage factor $k$ | 1.96 | 1.96 | 1.96 | 1.96 | 1.96 | 1.96 |
| **Expanded uncertainty $u_{exp\text{-}V}$** | **1.858** | **1.876** | **1.840** | **1.782** | **1.788** | **1.777** |

the DAQ device, $u_{B\text{-}DAQ}$, due to the large sensitivity coefficient which is equal to the PQ signal amplifier's amplification. This component of the measurement uncertainty can be significantly reduced by using the PQ signal amplifier at its ±10 V range, thereby reducing its amplification as well as the Type B uncertainty of the DAQ device.

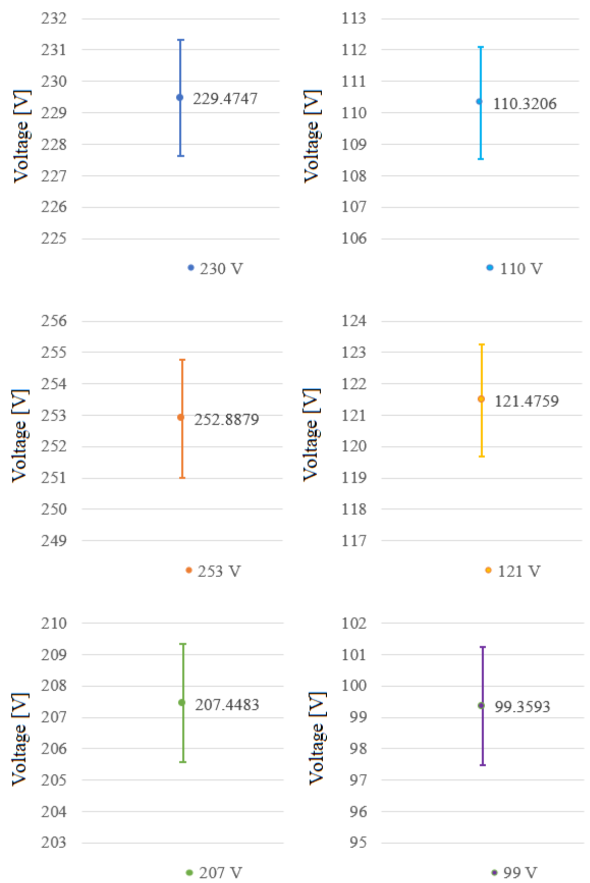


Figure 3: Graphical representation of the expanded uncertainty of the PQ generator – RMS voltage

### 3.2. Frequency Uncertainty

The measurement setup for frequency calibration of the PQ disturbance generator is the same as the setup used for calibration of the voltage RMS and consists of the NI USB-6218 DAQ device used to generate the input voltage signals for the amplifier and a 6½-digit digital multimeter Fluke 8846A for measurement of the amplifier output frequency values. The components of the measurement uncertainty budget for the generator frequency are presented in Table 4.

For calibration of the frequency, two measurement points are taken: 50 Hz and 60 Hz. The amplifier is once again set to the ±5 V input voltage range. The output of the DAQ device is set to a constant RMS value: 2.891 V, corresponding to 230 V at the output of the amplifier. The signal is generated at a sampling rate of 25 kS/s. For each measurement point, 10 measurements are taken at five-minute time intervals between two successive measurements. The average measured frequency values and the calculated standard deviations for each measurement point are presented in Table 5.

Similar to the measurement uncertainty of the output RMS voltage, the calculation of the standard measurement uncertainty of the frequency of the output voltage of the PQ disturbance generator includes Type A and Type B (DAQ device accuracy and resolution, multimeter uncertainty and resolution) uncertainty.

The standard deviation of the mean is calculated according to statistical methods applied on the measurement results, using the equation:

$$u_A = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}\left(f_i - f_{avg}\right)^2} \quad . \qquad (12)$$

Type B measurement uncertainties are calculated according to data and accuracies provided by the specifications of the applied instruments. According to instrument specifications, the multimeter absolute uncertainty for the frequency range of 40 Hz – 300 kHz and RMS voltage range from 100 mV – 1000 V is defined as $\Delta f_{DMM} = \pm$ (0.01 % of measurement). The multimeter resolution for the same range is $f_{DMM\text{-}res} = 0.0001$ Hz, therefore the corresponding DMM Type B uncertainty $u_{B\text{-}DMM}$ is calculated as:

Table 4: Measurement uncertainty budget – frequency

| Source | Type | Notation | Sensitivity coefficients | Probability distribution | Divisor | Degrees of freedom |
|---|---|---|---|---|---|---|
| Standard deviation (repeatability) | A | $u_A$ | 1 | Normal | 1 | 9 |
| DMM accuracy | B | $u_{B1}$ | 1 | Uniform | 1/√3 | ∞ |
| DMM resolution | B | $u_{B2}$ | 1 | Uniform | 1/√3 | ∞ |
| DAQ accuracy | B | $u_{B3}$ | 2500 at 50 Hz<br>3600 at 60 Hz | Uniform | 1/√3 | ∞ |
| DAQ resolution | B | $u_{B4}$ | 2500 at 50 Hz<br>3600 at 60 Hz | Uniform | 1/√3 | ∞ |

Table 5: Measurement results and calculated standard deviations (ST. DEV) – PQ generator frequency values

| | **50 Hz** ***f*** **[Hz]** | **60 Hz** ***f*** **[Hz]** |
|---|---|---|
| $f_{avg}$ [Hz] | 49.9992 | 59.9989 |
| ST. DEV | $0.185 \cdot 10^{-3}$ | $0.237 \cdot 10^{-3}$ |
| ST. DEV / $\sqrt{n}$ | $0.586 \cdot 10^{-4}$ | $0.748 \cdot 10^{-4}$ |

$$u_{B-DMM}^2 = u_{B1}^2 + u_{B2}^2 \ . \tag{13}$$

$$u_{B-DMM}^2 = \left(\frac{\Delta f_{DMM}}{\sqrt{3}}\right)^2 + \left(\frac{1}{2}\frac{f_{DMM-res}}{\sqrt{3}}\right)^2 \ . \tag{14}$$

Type B measurement uncertainties of the DAQ device arise as a result of the timing accuracy and timing resolution of the device. According to the device specification, the timing accuracy is defined as $\Delta T_{DAQ}$ = (50 ppm of sample rate). The sampling rate $S_r$ = 25 kS/s. The timing resolution of the DAQ device is $T_{DAQ\text{-}res}$ = 50 ns. Because the timing accuracy and resolution are defined as units of time, the sensitivity coefficients for their respective uncertainties, $c_3$ and $c_4$ need to be determined. Equation (15) shows the dependence between the frequency of the generated signal $f$ and its period $T_{sig}$:

$$f = \frac{1}{T_{sig}} \ . \tag{15}$$

The sensitivity coefficients for the Type B uncertainties of the DAQ device, $c_3$ and $c_4$, can be calculated using the following equation:

$$\frac{\partial f}{\partial T} = \frac{1}{T_{sig}^2} = f^2 = c_3 = c_4 \ . \tag{16}$$

Hence, the sensitivity coefficients $c_3$ and $c_4$ are equal to the square of the generated signal's frequency.

The DAQ device Type B uncertainty $u_{B\text{-}DAQ}$ is calculated as follows:

$$u_{B-DAQ}^2 = c_3^2 u_{B3}^2 + c_4^2 u_{B4}^2 \ . \tag{17}$$

$$u_{B-DAQ}^2 = f^4\left(\frac{\Delta T_{DAQ}}{\sqrt{3}}\right)^2 + f^4\left(\frac{1}{2}\frac{T_{DAQ-res}}{\sqrt{3}}\right)^2 \ . \tag{18}$$

The combined frequency measurement uncertainty $u_{c\text{-}f}$ is calculated using the previously calculated individual Type A and Type B uncertainties, according to the following equation:

$$u_{c-f} = \sqrt{u_A^2 + u_{B-DMM}^2 + u_{B-DAQ}^2} \ . \tag{19}$$

The number of overall effective degrees of freedom $\nu_{eff}$ for the combined uncertainty is calculated using the Welch-Satterthwaite equation (10). The number of effective degrees of freedom for the combined uncertainty of both measurement points is a large number and can be considered as infinity ($\nu_{eff} = \infty$).

The expanded measurement uncertainty of the frequency of the PQ disturbance generator output voltage $u_{exp\text{-}f}$ is calculated for a confidence interval of 95 %. The coverage factor that corresponds to this confidence interval and effective degrees of freedom $\nu_{eff} = \infty$, adjusted according to the Student's t-distribution table is k = 1.96.

$$u_{exp-f} = k u_{c-f} = 1.96 \cdot u_{c-f} \ . \tag{20}$$

The standard uncertainty for each of the uncertainty components, as well as the combined and expanded uncertainty for each of the measurement points are presented numerically in Table 6. The expanded uncertainty is presented graphically in Figure 4.

The relative measurement uncertainty of the frequency of the PQ disturbance generator for both measurement points is less than 0.5 %. The largest contributing component to the combined measurement uncertainty of the frequency is also the Type B uncertainty of the DAQ device $u_{B\text{-}DAQ}$. This component can only be reduced by using a DAQ device with better timing accuracy and resolution.

When evaluating the frequency uncertainty of a PQ generator, higher order harmonics should be taken into account, however, within the scope of this paper, the authors limited the analysis only to the fundamental frequency.

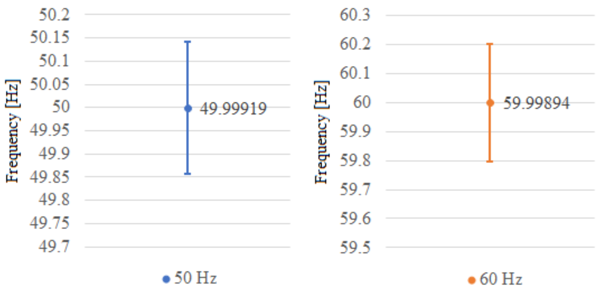


Figure 4: Graphical representation of the expanded uncertainty of the PQ generator – frequency

Table 6: Standard, combined and expanded measurement uncertainty calculations – frequency

| **Source** | **Standard Uncertainty [Hz]** | |
|---|---|---|
| | **50 Hz** | **60 Hz** |
| $u_A$ | $5.859 \cdot 10^{-5}$ | $7.483 \cdot 10^{-5}$ |
| $u_{B\text{-}DMM}$ | $2.887 \cdot 10^{-3}$ | $3.464 \cdot 10^{-3}$ |
| $u_{B\text{-}DAQ}$ | $7.217 \cdot 10^{-2}$ | $1.039 \cdot 10^{-1}$ |
| Combined uncertainty $u_{c\text{-}f}$ | $7.223 \cdot 10^{-2}$ | $1.040 \cdot 10^{-1}$ |
| Effective degrees of freedom $\nu_{eff}$ | ∞ | ∞ |
| Coverage factor $k$ | 1.96 | 1.96 |
| Expanded uncertainty $u_{exp\text{-}f}$ | $1.416 \cdot 10^{-1}$ | $2.038 \cdot 10^{-1}$ |

Considering the metrological characteristics of the designed PQ generator obtained with its calibration, the system can be used as a PQ event simulator for research purposes and for testing and optimization of PQ event classifiers. However, in order to use this PQ generator as a reference instrument in testing PQ analyzers for example, its voltage and frequency measurement uncertainties need to be improved as per the recommendations stated in the preceding text.

## 4. SUMMARY

The obtained results have shown that the relative measurement uncertainty of the PQ generator for all reference points is satisfactory. Hence it can be used as a simulator of PQ signals for research purposes, for instance for testing, optimization and improvement of PQ classifiers. However, the accuracy of the generator is not high enough to be used for testing of professional PQ monitoring instruments. The paper provides guidelines on how the measurement uncertainty can be improved.

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