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Power system frequency and rate-of-change of frequency measurement under steady-state and dynamic conditions by means of electronic instruments

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ABSTRACT
In this paper, the accuracy of the power system frequency measurement achieved by means of two commonly used electronic instruments, which are a universal counter and a bench top digital multimeter, is investigated under steady-state and dynamic conditions in the case of synthetized and real-life power system signals. Moreover, the accuracy of the rate-of-change of frequency estimates achieved by means of the frequency measurements is analysed. The results obtained by both instruments are compared with each other. From this comparison some remarks are drawn.

Section: RESEARCH PAPER

Keywords: electronic instruments; frequency and rate-of-change of frequency measurement; power system signals; steady-state and dynamic conditions

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1. INTRODUCTION

One of the most important parameters of an electrical waveform is its frequency. It is often used in the modern power systems for control and protection purposes. In these applications the frequency should be estimated in real-time with high accuracy. To this aim there have been proposed different time-domain and frequency-domain algorithms [1]-[5]. To achieve high accurate frequency estimates of real-life electrical waveforms they compensate the contribution of the spectral interference due to the frequency image component, harmonics, and inter-harmonics, and reduce the contribution of the wideband noise. Another possibility to estimate the frequency is to use electronic instruments. The commonly used instruments for frequency measurement are the Universal Counters (UCs) and the Digital MultiMeters (DMMs). Most of these instruments measure the frequency by using the technique of reciprocal universal counter. The aim of this paper is to investigate the accuracy of the frequency estimates achieved by using two such instruments under different steady-state and dynamic conditions in the case of synthetized and real-life power system signals. The steady-state conditions are the off-nominal frequency, harmonics, and Out-Of-Band Interferences (OOBI), while the dynamic conditions are the Amplitude Modulation (AM) and Phase Modulation (PM). The related test signals are those specified in the Standard IEC/IEEE 60255-118-1:2018 – Synchrophasor for power systems – Measurements for both *P-class* and *M-class* Phasor Measurement Unit (PMU) performance [6] and combination of these signals without or with noise. The used instruments are the reciprocal UC BK1823A [7] and the DMM Keysight 34465A [8]. The BK1823A has fixed Gate Time (*GT*) values, which are 0.01 s, 0.1 s, 1 s, and 10 s. The Keysight 34465A is a bench top DMM with 6½ digits. It measures frequency by using the principle of the reciprocal universal counter. The Keysight 34465A also has fixed *GT* values, which are the same as in the case of BK1823A and, supplementary, 1 ms value. It should be remarked that the price of the Keysight 34465A is higher (about four-times higher) than that of the BK1823A since it is able to accurately measure more quantities.

Also, the Rate-Of-Change Of Frequency (ROCOF) parameter is estimated by means of the obtained frequency estimates. As accuracy parameters the Frequency Error (FE) and the Rate of change of the Frequency Error (RFE) or the ROCOF error are used. The FEs and RFEs achieved by both instruments at the same GT are compared with each other.

This paper is an extended version of the work performed in [9]. Thus, more signal tests are considered in the steady-state conditions for a better appreciation of accuracy of the frequency and *ROCOF* measurements achieved by both used instruments. In addition, the AM and PM conditions have been considered and more experimental results with real-life signals are performed.

The analysis performed in this work is very important since it allows the researchers to compare the accuracies of the proposed frequency estimators also with those achieved using the above instruments. The results provided by these instruments can be used also as reference values. The measurements performed in this work can be easily reproduced.

2. MEASUREMENTS PERFOMED ON SYNTETIZED SIGNALS

The nominal frequency is f_0 = 50 Hz. The measured frequency is denoted by f_x and the true frequency by f.

For both instruments the *GT* is fixed to 0.01 s or 0.1 s, in order to achieve a fast measurement. The frequencies measured by the BK1823A are achieved via an RS232 interface using the software developed by the manufacturer. In the case of the Keysight 34465A the measured frequencies are achieved via an USB interface by means of the PathWave BenchVue software developed by Keysight [10]. For the range 10 - 100 Hz the frequency accuracies specified in the instruction manuals of the BK1823A and Keysight 34465A are ± (*time base error* + *resolution* + 1 *count*) and ± (0.03% *of reading*), respectively [7], [8]. The time base error of the BK1823A is equal to 5 ppm/year, while for the considered frequency range the resolution is equal to 1 mHz when *GT* = 0.01 s and 0.1 mHz when *GT* = 0.1 s [7]. Thus, when a frequency close to 50 Hz is measured by the Keysight 34465A the achieved accuracy is about ±15 mHz, and about ± 2.25 mHz when *GT* = 0.01 s and ± 0.45 mHz when *GT* = 0.1 s in the case of using the BK1823.

Unfortunately, the time between two successive readings, which is available for the user, is not the same, and so, we cannot achieve a fixed reporting rate by any of these instruments. For example, when *GT* = 0.01 s there are 4 - 5 readings/s in the case of the BK1823A, and 14 - 16 readings/s in the case of the Keysight 34465A, in which the times between successive readings are not always the same.

The test signals are provided by the Keysight EDU33212A function/arbitrary waveform generator [11]. That generator has the facility to combine the signals generated at both outputs into one signal. That facility is used in this work to generate a sinewave affected by other tones such as harmonics and inter-harmonic and noise. The Keysight EDU33212A generator has a very high frequency stability, of about ± (1 *ppm of setting*) for the frequencies used in the performed tests. Therefore, we will consider that the true frequency is equal to the setting one.

In the steady-state and AM conditions the parameter *FE*, expressed in Hz, is computed by the expression:

$$FE_k = f_\mathrm{x}(t_k) - f, (k = 1, 2, \ldots, M), \quad (1)$$

where $f_\mathrm{x}(t_k)$ is the frequency measured at the kth discrete time t_k and M is the acquisition length, while, in the case of the PM condition the parameter *FE* is given by the expression:

$$FE_k = f_\mathrm{xd}(t_k) - \hat{f}_\mathrm{xd}(t_k), (k = 1, 2, \ldots, M), \quad (2)$$

where $f_\mathrm{xd}(t_k) = f_\mathrm{x}(t_k) - f_0$ is the frequency deviation at the kth discrete time, and $\hat{f}_\mathrm{xd}(t_k)$ is its estimate. In the performed PM test, the ideal frequency deviation is given by:

$$f_\mathrm{xd,ideal}(t_k) = -2\,\pi\,k_\mathrm{p}\,f_\mathrm{m} \sin(2\,\pi\,f_\mathrm{m}\,t_k)\,, (k = 1, 2, \ldots, M) \quad (3)$$

in which f_m is the modulation frequency and k_p is the phase angle modulation factor.

The estimate $\hat{f}_\mathrm{xd}$ is achieved by means of the three-parameter sine-fit algorithm [12], [13] applied to the signal $f_\mathrm{xd}(t_k)$, in which the frequency f_m and the times t_k, k = 1, 2,…, M are known.

In the steady-state and AM conditions the frequency is not changed and so, the parameter *RFE*, expressed in Hz/s, is equal to the parameter *ROCOF*, and they are computed as:

$$RFE_k = ROCOF_k = \frac{f_\mathrm{x}(t_{k+1}) - f_\mathrm{x}(t_k)}{T_{k+1,k}}, (k = 1, 2, \ldots, M-1)\,, \quad (4)$$

where $T_{k+1,\,k}$ is the time between the discrete times t_{k+1} and t_k, while in the PM condition the parameter *RFE* is computed as:

$$RFE_k = \frac{\hat{f}_\mathrm{xd}(t_{k+1}) - \hat{f}_\mathrm{xd}(t_k)}{T_{k+1,k}}, (k = 1, 2, \ldots, M-1)\,. \quad (5)$$

Then, the maximum of the absolute value of the magnitudes of the parameters *FE* and *RFE*, $|FE|_\mathrm{max}$ and $|RFE|_\mathrm{max}$, are computed.

The amplitude of the generated signals is equal to 4 V. In the case of noisy signals, a Gaussian noise of 9 mV effective value is added to the generated signals. This ensures a Signal-to-Noise Ratio (*SNR*) of the analysed signals of about 50 dB. In the case of BK1823A the test signals with added noise or affected by inter-harmonics or amplitude modulation, should be attenuated (1:10) to achieve accurate frequency measurements.

In the following we will present the results achieved by both instruments under the considered conditions.

2.1. Steady-state conditions

In these tests the parameters FE and RFE are computed by (1) and (4), respectively. In each test there are measured M = 1000 values of signal frequency.

a) off-nominal frequency condition

The test signals are sinewaves of 45 Hz, 48 Hz, 50 Hz, 52 Hz, and 55 Hz frequencies provided by the signal generator without and with added noise. *GT* is equal to 0.01 s.

The results achieved by both instruments are given in Table 1. Moreover, in Table 2 and Table 3, there are given the mean and standard deviation values of the frequency and *ROCOF* measurements achieved in the case of the sinewaves with added noise.

Table 1. $|FE|_\mathrm{max}$ and $|RFE|_\mathrm{max}$ achieved by both instruments when *GT* = 0.01 s under off-nominal frequency condition. Sinewaves amplitude equal to 4 V. Sinewaves with added noise are attenuated in the case of BK1823A.

Frequency (Hz)	Added noise	UC BK1823A		DMM Keysight 34465A	
		$\|FE\|_\mathrm{max}$ (mHz)	$\|RFE\|_\mathrm{max}$ (Hz/s)	$\|FE\|_\mathrm{max}$ (mHz)	$\|RFE\|_\mathrm{max}$ (Hz/s)
45	No	2.0	0.009	17.0	0.41
	Yes	87	0.533	50	1.14
48	No	3.0	0.017	15.0	0.36
	Yes	100	0.620	48	1.25
50	No	2.0	0.014	13.0	0.32
	Yes	106	0.649	54	1.30
52	No	3.0	0.014	16.0	0.38
	Yes	100	0.585	52	1.33
55	No	2.0	0.009	20.0	0.46
	Yes	115	0.750	61	1.40

Table 2. Mean and standard deviation values of the frequency measurements achieved by both instruments when *GT* = 0.01 s under off-nominal frequency condition in the case of sinewaves with added noise. Sinewaves amplitude equal to 4 V. Sinewaves attenuated in the case of BK1823A.

Frequency (Hz)	BK1823A		Keysight 34465A	
	Mean (Hz)	Std. (Hz)	Mean (Hz)	Std. (Hz)
45	45.0008	0.0318	45.0010	0.0161
48	47.9995	0.0346	48.0003	0.0171
50	49.9963	0.0353	50.0010	0.0180
52	51.9995	0.0354	52.0008	0.0184
55	54.9997	0.0402	55.0018	0.0206

Table 3. Mean and standard deviation values of the *ROCOF* measurements achieved by both instruments when *GT* = 0.01 s under off-nominal frequency condition in the case of sinewaves with added noise. Sinewaves amplitude equal to 4 V. Sinewaves attenuated in the case of BK1823A.

Frequency (Hz)	BK1823A		Keysight 34465A	
	Mean (Hz/s)	Std. (Hz/s)	Mean (Hz/s)	Std. (Hz/s)
45	0.00	0.19	0.00	0.38
48	0.00	0.21	0.00	0.42
50	0.00	0.22	0.00	0.44
52	0.00	0.22	0.00	0.43
55	0.00	0.25	0.00	0.48

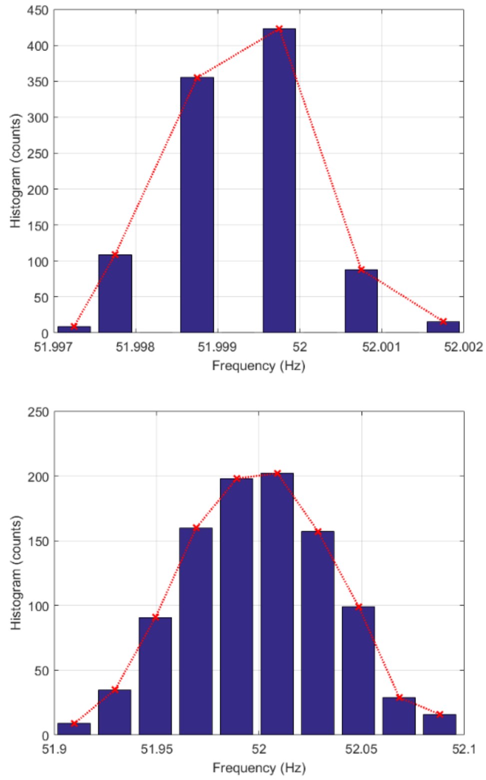
From the results given in Table 1 it follows that in the case of sinewaves without added noise both frequency and *ROCOF* are more accurate measured by using the BK1823A than the Keysight 34465A. The achieved errors are close to the theoretical frequency accuracies. Conversely, in the case of sinewaves with added noise the frequency is more accurately measured by Keysight 34465A, while the *ROCOF* by using the BK1823A. Also, from Table 1 it can be observed that the BK1823A is less robust to wideband noise. In this case, as it follows from Tables 2 and 3 the standard deviations of the frequency measurements achieved by the Keysight 34465A are smaller than those achieved by the BK1823A, and inverse in the case of the *ROCOF* measurements. Conversely, the mean values of frequency and *ROCOF* measurements achieved by both instruments are close.

Figure 1 and Figure 2 show the histograms corresponding to the frequency $f = 52$ Hz achieved for the frequency measurements obtained by the BK1823A and Keysight 34465A, respectively, in in the cases of sinewaves without and with added noise.

In Figure 1 it can be observed that the BK1823A provides a much higher number of different frequency values in the case of sinewaves with added noise than without added noise, when only a limited number of frequency values are achieved. From Figure 2 it follows that this behavior is not achieved when the frequency is measured by the Keysight 34465A, when many different frequency values have been achieved in both cases.

Also, in Figure 1 and Figure 2 it can be observed that by adding noise, the ranges of the frequencies measured by both instruments increase. The above observations hold also for the *ROCOF* estimates.

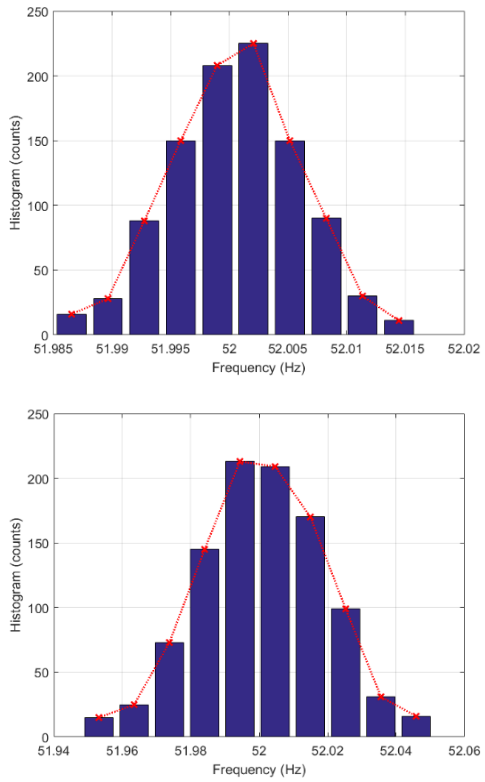
The skewness and Kurtosis coefficients for the frequencies measured by the BK1823A and Keysight 34465A, with histograms shown in Figure 1(b) and Figure 2(b), are 0.073 and 2.70 and -0.07 and 2.94, respectively. Since the Kurtosis coefficient for the results achieved by the Keysight 34465A is much closer to 3, it follows that the distribution shape of these results is much close to a normal one.



a)

b)

Figure 1. Histograms of the frequency measurements achieved by the BK1823A in the case of sinewaves a) without and b) with added noise when *GT* = 0.01 s and *f* = 52 Hz. *M* = 1000 measurements.



a)

b)

Figure 2. Histograms of the frequency measurements achieved by the Keysight 34465A in the case of sinewaves a) without and b) with added noise when *GT* = 0.01 s and *f* = 52 Hz. *M* = 1000 measurements.

Table 4. $|FE|_{max}$ and $|RFE|_{max}$ achieved by both instruments when $GT = 0.01$ s under harmonics condition. Sinewaves and harmonics amplitudes equal to 4 V and 0.4 V, respectively. Signals with added noise are attenuated in the case of BK1823A.

Test	UC BK1823A		DMM Keysight 34465A	
	$|FE|_{max}$ (mHz)	$|RFE|_{max}$ (Hz/s)	$|FE|_{max}$ (mHz)	$|RFE|_{max}$ (Hz/s)
2nd harmonic	2.0	0.013	15.0	0.36
3rd harmonic	2.0	0.013	11.0	0.27
5th harmonic	2.0	0.017	9.0	0.23
7th harmonic	2.0	0.013	8.0	0.19
3rd, 5th, and 7th harmonics	2.0	0.017	9.0	0.19
3rd and 5th harmonics	2.0	0.014	9.0	0.22
3rd and 5th harmonics and noise	79	0.452	40	0.96

b) harmonics condition

The test signals are harmonically distorted sinewaves of 50 Hz frequency. Firstly, a single harmonic of 2nd, 3rd, 5th, or 7th order is added to the sinewave. Then, harmonically distorted sinewaves affected by the 3rd, 5th, and 7th harmonics, and 3rd and 5th harmonics without and with added noise are generated by using another Keysight EDU33212A generator and a passive adder in delta connection with 50 Ω resistances. In the performed tests the amplitude of each considered harmonic is equal to 10 % of the fundamental amplitude (i.e., 0.4 V). It is worth noticing that when the passive adder is used the values of the sinewaves and harmonics amplitudes, and the noise effective value are twice higher than those used without the passive adder. GT is equal to 0.01 s.

The results achieved by both instruments under the above conditions are given in Table 4.

From the results given in Table 4 it follows that in the case of signals without added noise the frequency and *ROCOF* measurements achieved by using the BK1823A are more accurate than those achieved by using the Keysight 34465A. Conversely, in the case of signals with added noise the frequency is more accurate measured by Keysight 34465A, while the *ROCOF* by using the BK1823A.

Also, by comparing the results given in Table 1 when $f = 50$ Hz with those given in Table 4 it follows that the harmonics has a very small contribution on the frequency measurements achieved by both instruments.

c) out-of-band interference (OOBI) condition

Two test signals which contain the fundamental component, and an inter-harmonic are considered. In the first test signal the frequency of the fundamental component is equal to 47.5 Hz, while that of the inter-harmonic is equal to 25 Hz. In the second test signal the frequency of the fundamental component is equal to 52.5 Hz, while that of the inter-harmonic is equal to 75 Hz.

The inter-harmonics amplitude is equal to 10 % of the amplitude of the fundamental component (i.e., 0.4 V). The results achieved when GT = 0.01 s and 0.1 s are reported in Table 5.

When $GT = 0.1$ s the errors achieved by both instruments are smaller as compared with those achieved when $GT = 0.01$ s, but they are still high.

A further reduction of the achieved errors can be made by filtering. To this aim a six-order band-pass filter has been considered. It consists of three two-order band-pass filters connected in series. Each two-order band-pass filter was

Table 5. $|FE|_{max}$ and $|RFE|_{max}$ achieved by both instruments when $GT = 0.01$ s and GT = 0.1 s under out-of-band interference condition. Sinewaves and inter-harmonics amplitudes equal to 4 V and 0.4 V, respectively. Signals are attenuated in the case of BK1823A.

Sinewave and interharmonics frequencies and GT	UC BK1823A		DMM Keysight 34465A	
	$|FE|_{max}$ (mHz)	$|RFE|_{max}$ (Hz/s)	$|FE|_{max}$ (mHz)	$|RFE|_{max}$ (Hz/s)
47.5 Hz & 25 Hz $GT = 0.01$ s	1121.0	8.23	1582.0	57.49
47.5 Hz & 25 Hz $GT = 0.1$ s	204.6	1.75	291.0	3.00
52.5 Hz & 75 Hz $GT = 0.01$ s	1620.0	6.30	1630.0	55.74
52.5 Hz & 75 Hz $GT = 0.1$ s	306.2	2.10	266.0	2.29

implemented through the universal active filter UAF42 [14]. The band-pass of this filter is [40, 60] Hz (central frequency of 50 Hz and bandwidth equal to 20 Hz) and the noninverting pole-pair 1 (PP1) subcircuit is used [14] (see Figure 3). The values of the resistances with 1% tolerance have been achieved through FILTER42 program developed by Burr-Brown for the design of the active filters with the filter UAF42 [15].

In Figure 4 there are presented the spectra of the input (Figure 4(a)) and the output (Figure 4(b)) signals of the implemented filter in the case of a sinewave of 52.5 Hz affected by an inter-harmonic of 75 Hz. They are achieved by using the EDUX1002G digital storage oscilloscope [16].

From Figure 4(b) it follows that the inter-harmonic component has been rejected by the implemented filter. The same behaviour has been achieved in the case of the other signals where the inter-harmonics and harmonics are rejected by the implemented filter.

In Table 6 there are given the results achieved when the filter is used and $GT = 0.1$ s. In addition, to the sinewaves affected by one of the above inter-harmonics the 3rd and 5th harmonics of amplitude 0.4 V and 150 Hz and 250 Hz frequencies, respectively, have been added by using the same experimental set-up as in the harmonics condition. The results achieved in the case of these signals are also given in Table 6.

By filtering the accuracy of the frequency and *ROCOF* measurements achieved by both BK1823A and Keysight 34465A increases very much. The maximum of the errors achieved when the harmonics are added are little bit higher than those achieved in the presence of harmonics. Also, it can be observed that the maxima of the errors achieved by both instruments are close.

Moreover, the histograms corresponding to the sinewave of 52.5 Hz frequency affected by an inter-harmonic of 75 Hz for

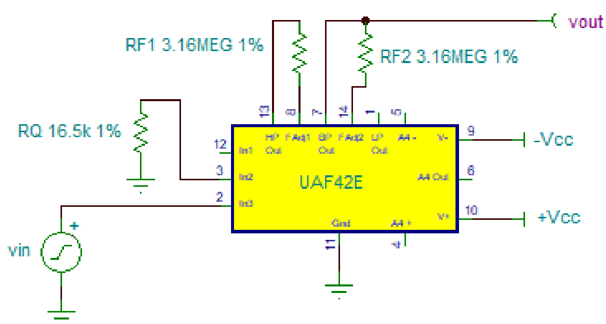


Figure 3. Two-order band-pass filter implemented by means of the universal active filter UAF42. The noninverting PP1 subcircuit is used [14]. The band-pass of the filter is [40, 60] Hz.

a)

b)

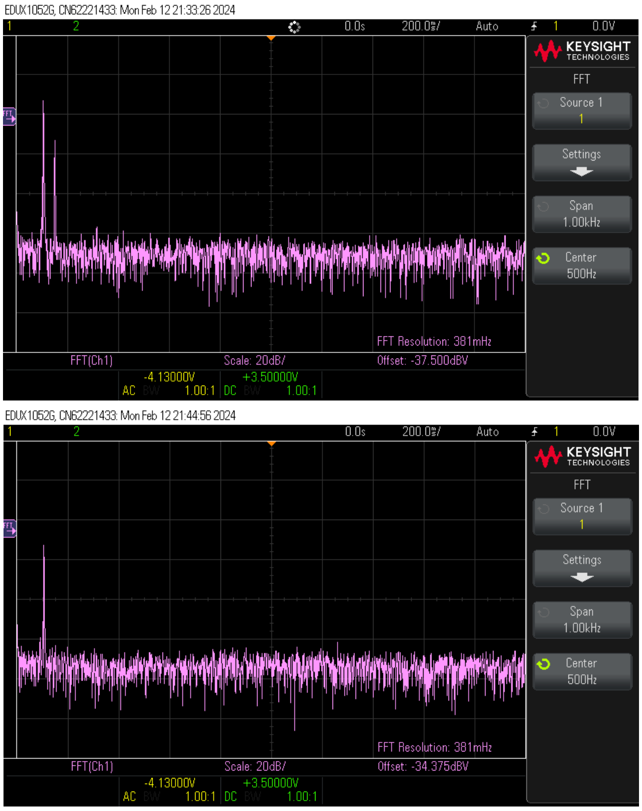


Figure 5. Spectra of the a) input and the b) output signals of the implemented filter in the case of a sinewave of 52.5 Hz affected by an inter-harmonic of 75 Hz.

the frequency measurements achieved by both instruments when the filtering is applied, and $GT = 0.1$ s are shown in Figure 5.

In Figure 5 it can be observed that many different frequency values are achieved by both instruments.

2.2. Dynamic conditions

The test signals are amplitude and phase modulated sinewaves. The used AM and PM signals have the following parameters [6]: signal frequency $f = 50$ Hz, modulation frequency $f_m = 2$ Hz or 5 Hz, amplitude modulation factor $k_a = 0.1$, and phase modulation factor $k_p = 0.1$ rad. In the case of AM signals the parameters *FE* and *RFE* are computed by (1) and (4), respectively, while in the case of PM signals by (2) and (5), respectively. GT is equal to 0.01 s. In the AM test there are measured $M = 1000$ values of signal frequency, while in the PM test M is equal to the number of frequencies measured in one minute.

Table 6. $|FE|_{max}$ and $|RFE|_{max}$ achieved by both instruments when the filter is used and $GT = 0.1$ s under out-of-band interference condition. Sinewaves amplitudes equal to 4 V and inter-harmonics and harmonics amplitudes equal to 0.4 V. Signals are attenuated in the case of BK1823A.

Sinewave, inter-harmonics, and harmonics frequencies	UC BK1823A		DMM Keysight 34465A	
	$\|FE\|_{max}$ (mHz)	$\|RFE\|_{max}$ (Hz/s)	$\|FE\|_{max}$ (mHz)	$\|RFE\|_{max}$ (Hz/s)
47.5 Hz & 25 Hz	15.4	0.10	12.0	0.12
52.5 Hz & 75 Hz	28.3	0.20	26.0	0.20
47.5 Hz & 25 Hz & 150 Hz & 250 Hz	20.9	0.14	16.0	0.15
52.5 Hz & 75 Hz & 150 Hz & 250 Hz	51.0	0.32	40.0	0.38

a)

b)

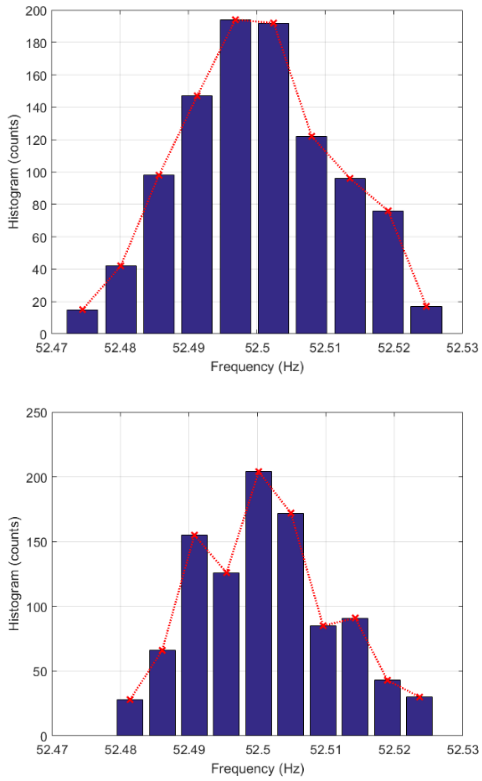


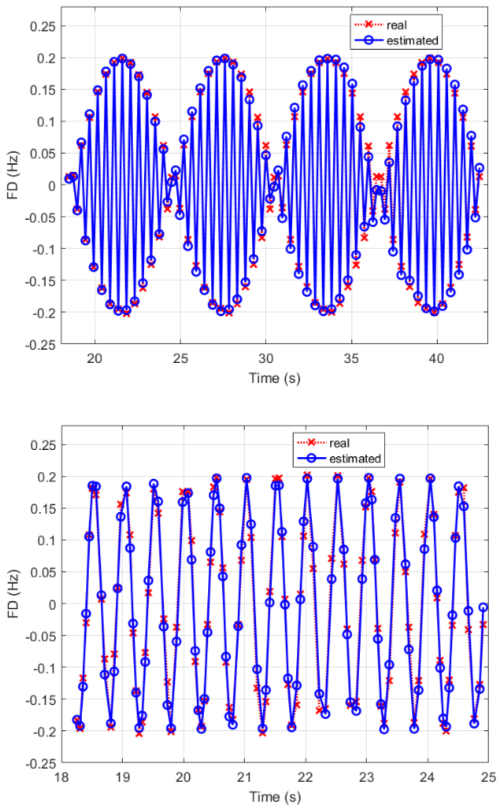
Figure 4. Histograms of the frequency measurements achieved by a) the BK1823A and b) the Keysight 34465A when $GT = 0.1$ s in the case of a sinewave of frequency $f = 52.5$ Hz affected by an inter-harmonic of 75 Hz applied to a six-order band-pass filter. The amplitude of inter-harmonic equal to 10 % of that of the fundamental component, $M = 1000$ measurements. Signals are attenuated in the case of BK1823A.

The results achieved by both instruments under AM and PM conditions are given in Table 7.

From the results given in Table 7 it follows that by using the BK1823A the frequency and *ROCOF* are more accurate measured than when the Keysight 34465A is used. The errors increase as the modulation frequency f_m increases and under the AM condition the achieved errors are much smaller than those achieved under the PM condition. Under the PM condition there is a small number of measured frequencies into one period, which decreases as f_m increases. Hence, the achieved estimation errors can be important, especially when the Keysight 34465A is used and $f_m = 5$ Hz. The above behavior can be seen in Figure 6 and Figure 7 where the real and estimated frequency deviations *FD*s achieved by the BK1823A and the Keysight 34465A when $f_m = 2$ Hz (Figure 6) and $f_m = 5$ Hz (Figure 7) are shown as a function of time.

Table 7. $|FE|_{max}$ and $|RFE|_{max}$ achieved by both instruments when $GT = 0.01$ s under AM and PM conditions. Modulation parameters are $f_m = 2$ Hz or 5 Hz and $k_a = 0.1$ and $k_p = 0.1$. AM signals are attenuated in the case of BK1823A.

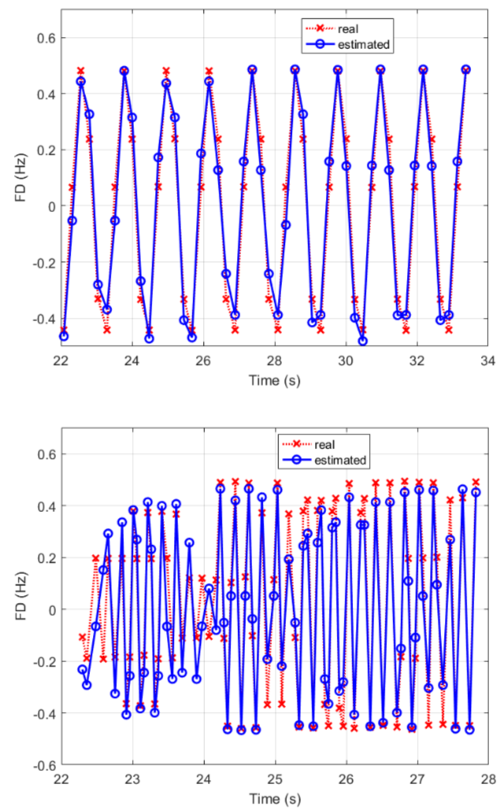
Test	UC BK1823A		DMM Keysight 34465A	
	$\|FE\|_{max}$ (mHz)	$\|RFE\|_{max}$ (Hz/s)	$\|FE\|_{max}$ (mHz)	$\|RFE\|_{max}$ (Hz/s)
AM ($f_m = 2$ Hz)	25.0	0.21	67.0	1.00
AM ($f_m = 5$ Hz)	44.0	0.23	53.0	1.88
PM ($f_m = 2$ Hz)	29.2	1.76	63.1	2.44
PM ($f_m = 5$ Hz)	134.6	2.90	393.7	13.4



a)

b)

Figure 6. Real and estimated *FD*s achieved by a) the BK1823A and b) the Keysight 34465A when *GT* = 0.01 s under PM conditions when f_m = 2 Hz.



a)

b)

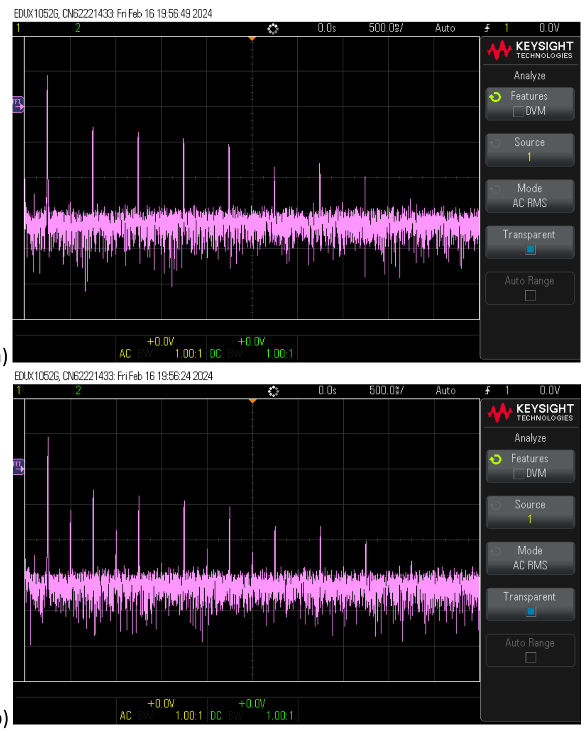
Figure 7. Real and estimated *FD*s achieved by a) the BK1823A and b) the Keysight 34465A when *GT* = 0.01 s under PM conditions when f_m = 5 Hz.

3. MEASUREMENTS PERFOMED ON POWER SIGNALS

Moreover, measurements of a real-life power system frequency and *ROCOF* by means of both instruments have been carried out. The analyzed signal has been achieved from the power system through a step-down voltage transformer. Also, a hair dryer is connected to the same power source. Figure 8 shows the spectra of the power signals obtained when the hair dryer is off (Figure 8(a)) and on (Figure 8(b)). In Figure 8 it can be observed that the hair dryer introduces also even harmonics in the signal spectrum. The most important ones are the 2nd and 4th harmonics. $M = 1000$ frequency measurements are performed by both instruments with $GT = 0.01$ s when the hair dryer is on. The statistical results of the frequency and *ROCOF* measurements achieved by using each instrument are given in Table 8 and Table 9.

From Table 8 it results that the mean values of the frequency measurements achieved by both instruments are very close. Also, the maximum differences between the mean and the extreme values of the frequencies achieved by the BK1823A and the Keysight 34465A are about 51 mHz and 63 mHz, respectively. Conversely, the statistical efficiency of the *ROCOF* measurements achieved by using the BK1823A is higher than that achieved by using the Keysight 34465.

Figure 9 and Figure 10 show the histograms of the frequency and *ROCOF* measurements achieved by both instruments. It can be observed that for both frequency and *ROCOF* there are many different measurement values achieved by each instrument. Furthermore, the skewness and Kurtosis coefficients of the performed data measurements have been computed. Thus, for the frequency measurements achieved by the BK1823A and the Keysight 34465A they are about -0.07 and 3.18 and -0.02 and 2.67, respectively, while for the *ROCOF* measurements they are about -0.10 and 3.20 and -0.07 and 2.97, respectively. Thus, the distributions shapes of data measurements are relatively close to a normal one.



a)

b)

Figure 8. Spectra of the real-life power system signals obtained when the used hair dryer is a) off and b) on.

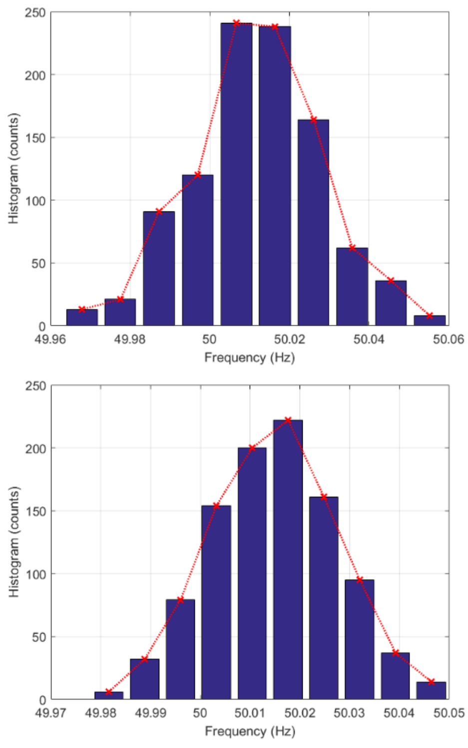
Table 8. Statistical results of the frequency measurements achieved by both instruments when *GT* = 0.01 s in the case of real-life power system signals obtained when the hair dryer is on.

Test	UC BK1823A	DMM Keysight 34465A
Minimum (Hz)	49.963	49.978
Maximum (Hz)	50.060	50.050
Mean (Hz)	50.012	50.015
Std. dev. (Hz)	0.016	0.013

Table 9. Statistical results of the *ROCOF* measurements achieved by both instruments when *GT* = 0.01 s in the case of real-life power system signals obtained when the hair dryer is on.

Test	UC BK1823A	DMM Keysight 34465A
Minimum (Hz)	-0.26	-0.81
Maximum (Hz)	0.26	0.70
Mean (Hz)	0.00	0.00
Std. dev. (Hz)	0.08	0.81

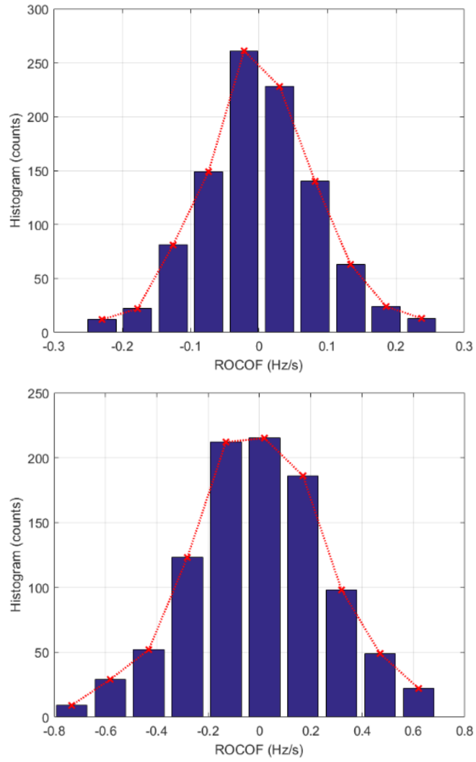
Moreover, the power signals have been modulated in amplitude by using the experimental set-up shown in Figure 11. It contains the ASLK PRO board [17] for the related multiplication and summation operations. The amplitude modulation factor k_a is equal to the $1/SF$, where SF is the Scale Factor of the MPY634 multiplier. SF is set to 10, by leaving the Scale Factor pin unconnected [18]. The modulation frequency is f_m = 5 Hz. The frequencies of the achieved AM signals are measured by both instruments with GT = 0.01 s and have been compared with those measured by another BK1823A with GT = 1 s, considered as reference values.



a)
b)

Figure 9. Histograms of the frequency measurements achieved by a) the BK1823A and b) the Keysight 34465A when *GT* = 0.01 s in the case of real-life power system signals obtained when the hair dryer is on. *M* = 1000 measurements.

The spectrum of a such AM signal is shown in Figure 12. It can be seen that all components (fundamental and harmonics) are modulated in amplitude.



a)
b)

Figure 10. Histograms of the *ROCOF* measurements achieved by a) the BK1823A and b) the Keysight 34465A when *GT* = 0.01 s in the case of real-life power system signals obtained when the hair dryer is on. *M* = 1000 measurements.

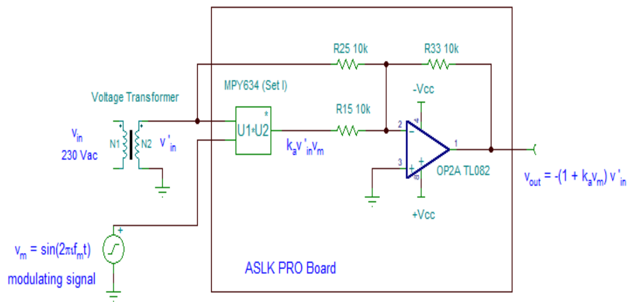


Figure 11. The experimental set-up used to achieve AM power signals.

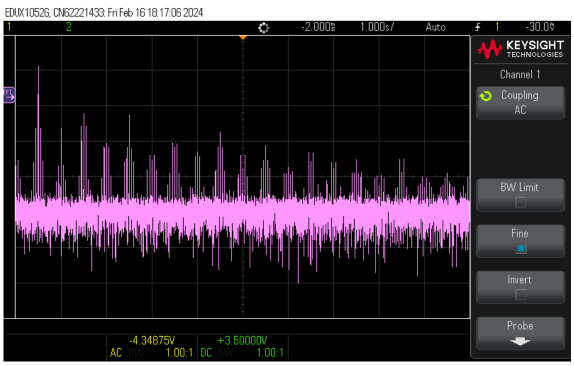
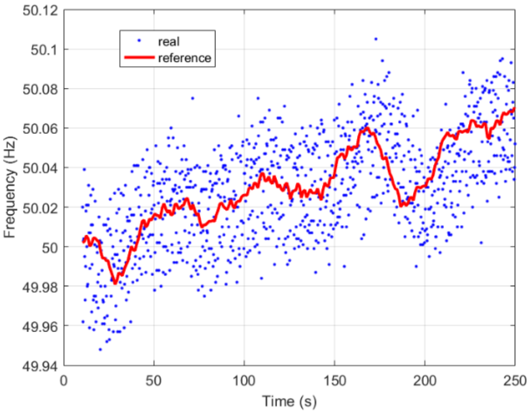
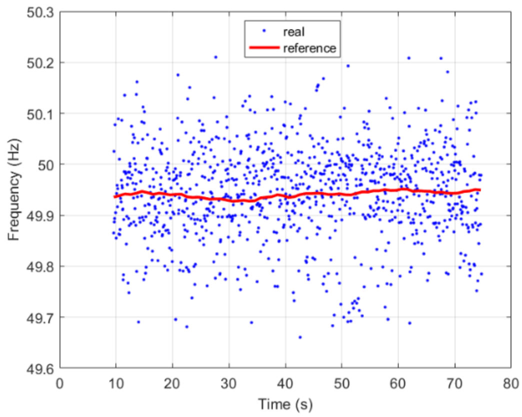


Figure 12. Spectrum of an AM power signal achieved used the experimental set-up shown in Figure 10.



a)



b)

Figure 13. Frequencies measured by a) the BK1823A and b) the Keysight 34465A and the reference BK1823A as a function of time in the case of the generated AM power signals. M = 1000 measurements are performed by each instrument with GT = 0.01 s. The reference BK1823A has GT = 1 s. Signals are attenuated in the case of BK1823A.

Figure 13 shows the frequencies measured by each instrument and the reference frequencies as a function of time. M = 1000 measurements have been performed by both instruments in the case of the generated AM power signals. The attenuation is used in the case of BK1823A.

In Figure 13 it can be observed that the frequencies measured by BK1823A exhibit a smaller difference as compared with the reference frequencies than those achieved when the Keysight 34465A is used.

4. CONCLUSIONS

In this work the power system frequency accuracies achieved by a reciprocal universal counter – BK1823A, and a bench top DMM - Keysight 34465A, have been compared with each other under different steady-state and dynamic conditions in the case of synthetized and real-life power system signals. As dynamic conditions the amplitude and phase modulations are considered. Moreover, the *ROCOF* parameter achieved based on the frequency measurements provided by both instruments at their reporting rates has been estimated. It has been shown that in most situations by using the BK1823A more accurate frequency and *ROCOF* measurements are achieved than when the Keysight 34465A is used. Also, it has been shown that the measurements achieved by using both instruments are not affected by harmonics, but they are very much affected by inter-harmonics. To avoid the contribution of the inter-harmonics on the frequency and *ROCOF* measurements the *GT* should be increased, and the analyzed signal should be filtered.

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