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Power System Frequency and ROCOF Measurement 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, are investigated under steady-state conditions in the case of synthetized and real-life power system signals. Moreover, the accuracy of the Rate-Of-Change Of Frequency (*ROCOF*) estimates achieved by means of the frequency measurements is analyzed. The results obtained by both instruments are compared with each other. In addition, from the achieved measurements some remarks are drawn.**

I. 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 accuracy, they compensate the contribution of the spectral interference due to the frequency image component, harmonics, and interharmonics, which affect any real-life electrical waveforms. Another possibility to estimate the frequency is to use electronic instruments. The commonly used instruments for frequency measurement are the reciprocal Universal Counters (UCs) and the Digital MultiMeters (DMMs). They measure the frequency by using the same technique. The aim of this paper is to investigate the accuracy of the frequency estimates achieved by using two such instruments under different steady-state conditions in the case of synthetized and real-life power system signals. These conditions are the off-nominal frequency, harmonics, and Out-Of-Band Interferences (OOBI). The used instruments are the reciprocal UC BK1823A [6] and the DMM Keysight 34465A [7]. The BK1823A has only 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 about four-times higher than that of the BK1823A.

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 *FE*s and *RFE*s achieved by both instruments are compared with each other.

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 such instruments. The presented measurements can be easily reproduced.

II. THE PERFORMED MEASUREMENTS

The nominal frequency is f_0 = 50 Hz. 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 BK1823 are acquired via an RS232 interface using the software developed by the manufacturer. In the case of the Keysight 34465A the measured frequencies are acquired via an USB interface by means of the PathWave BenchVue software developed by Keysight [8].

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. The average reporting rate for the BK1823A is about 4 readings/s, while for the Keysight 34465A it is about 15 readings/s.

The test signals are provided by the Keysight EDU33212A function/arbitrary waveform generator [9]. 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 a harmonic or an interharmonic. 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 each test there are measured M = 1000 values of signal frequency.

The parameter *FE* is computed by the expression:

$$FE_k(\text{Hz}) = f_k - f, k = 1, 2, \dots, M - 1 \qquad (1)$$

in which f_l is the lth measured frequency and f is the true frequency.

Since in the steady-state conditions the frequency is not changed the parameter RFE is equal to the parameter

ROCOF, which are computed as:

$$RFE_k \text{ (Hz/s)} = ROCOF_k \text{(Hz/s)}$$

$$= \frac{f_{k+1} - f_k}{T}, \; k = 1, 2, \ldots, M-1 \qquad (2)$$

where T is the time between two successive readings. Then, the maximum of the absolute value of the magnitudes of the parameters *FE* and *RFE*, $|FE|_{max}$ and $|RFE|_{max}$, are computed.

The amplitude of the generated sinewave is equal to 8 V.

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

A. Steady-state conditions

• off-nominal frequency condition

GT is equal to 0.01 s. The results achieved by both instruments at 45 Hz, 48 Hz, 50 Hz, 52 Hz, and 55 Hz frequencies are given in Table 1 and the histograms corresponding to the frequency f = 52 Hz achieved for the frequency measurements obtained by both instruments are shown in Fig. 1.

Table 1. $|FE|_{max}$ and $|RFE|_{max}$ achieved by both instruments when GT = 0.01 s under off-nominal frequency condition.

Frequency (Hz)	UC BK1823A		DMM Keysight 34465A	
	$\|FE\|_{max}$ (mHz)	$\|RFE\|_{max}$ (Hz/s)	$\|FE\|_{max}$ (mHz)	$\|RFE\|_{max}$ (Hz/s)
45	2.0	0.009	17.0	0.41
48	3.0	0.017	15.0	0.36
50	2.0	0.014	13.0	0.32
52	3.0	0.014	16.0	0.38
55	2.0	0.009	20.0	0.46

From the results given in Table 1 it follows that the frequency and *ROCOF* are more accurate measured by using the BK1823A than the Keysight 34465A. Moreover, from Fig. 1 it can be observed that the BK1823A provides a smaller number of different frequency values as compared with the Keysight 34465A. This observation holds also for the *ROCOF* estimates.

• harmonics condition

GT is equal to 0.01 s. The results achieved by both instruments in the case of the 2nd, 3rd, 5th, and 7th harmonics are given in Table 2. The amplitude of each considered harmonic is equal to 10% of the fundamental amplitude.

From the results given in Table 2 it follows that the frequency and *ROCOF* measurements achieved by using the BK1823A are more accurate than those achieved by using the Keysight 34465A. Also, by comparing the results given in Table 1 when f = 50 Hz with those given in Table 2 it follows that the harmonics has a very small contribution on the frequency measurements achieved by both instruments.

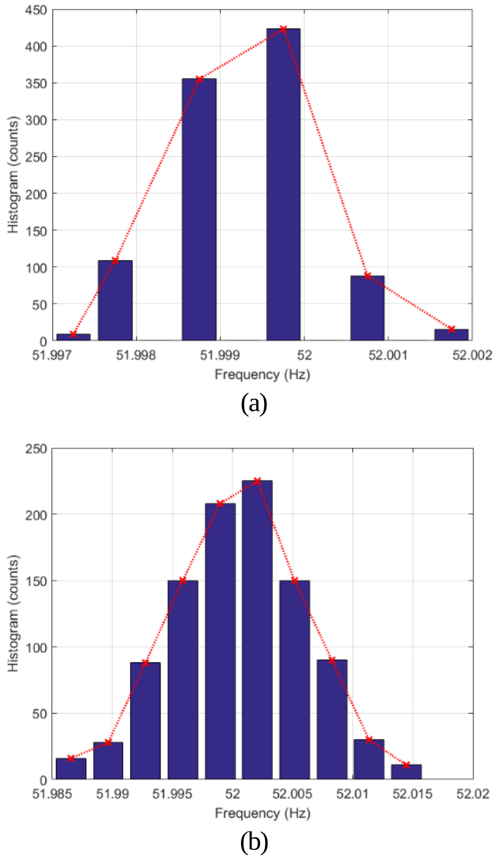


Fig. 1. Histograms of the frequency measurements achieved by the BK1823A (a) and the Keysight 34465A (b) when GT = 0.01 s and f = 52 Hz. M = 1000 measurements.

Table 2. $|FE|_{max}$ and $|RFE|_{max}$ achieved by both instruments when GT = 0.01 s under harmonics condition.

Harmonic	UC BK1823A		DMM Keysight 34465A	
	$\|FE\|_{max}$ (mHz)	$\|RFE\|_{max}$ (Hz/s)	$\|FE\|_{max}$ (mHz)	$\|RFE\|_{max}$ (Hz/s)
2nd	2.0	0.013	15.0	0.36
3rd	2.0	0.013	11.0	0.27
5th	2.0	0.017	9.0	0.23
7th	2.0	0.013	8.0	0.19

• out-of-band interference (OOBI) condition

Two test signals which contain the fundamental component and an interharmonic are considered. In the first test signal the frequency of the fundamental component is equal to 47.5 Hz, while that of the interharmonic 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 interharmonic is equal to 75 Hz.

The interharmonics amplitude is equal to 10% of the amplitude of the fundamental component. The results achieved when $GT = 0.01$ s and 0.1 s are reported in Table 3.

Table 3. $|FE|_{\max}$ and $|RFE|_{max}$ achieved by both instruments when $GT = 0.01$ s and $GT = 0.1$ s under out-of-band interference condition.

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	1123.0	8.27	1567.0	58.74
47.5 Hz & 25 Hz $GT = 0.1$ s	202.4	1.74	286.1	2.97
52.5 Hz & 75 Hz $GT = 0.01$ s	1774.0	7.10	1600.0	54.46
52.5 Hz & 75 Hz $GT = 0.1$ s	307.0	2.09	265.0	2.27

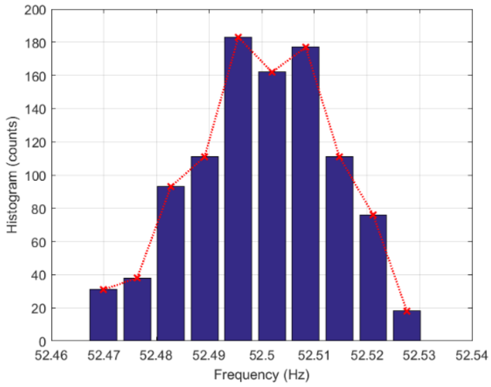
When $GT = 0.1$ s the errors achieved by both instruments are smaller as compared with those achieved when $GT = 0.01$ s, but they are still high. A further reduction of the achieved errors can be achieved by filtering. In Table 4 there are given the results achieved when $GT = 0.1$ s and a six-order band-pass filter is applied to the analyzed signal. That filter was obtained by connecting three two-order Butterworth band-pass filters in series. The two-order band-pass filter was implemented by means of the universal filter UAF42 [9]. The band-pass of this filter is [40, 60] Hz. The histograms corresponding to the second signal test for the frequency measurements achieved by both instruments are shown in Fig. 2.

Table 4. $FE|_{\max}$ and $|RFE|_{max}$ achieved by both instruments when $GT = 0.1$ s and using a filter under out-of-band interference condition.

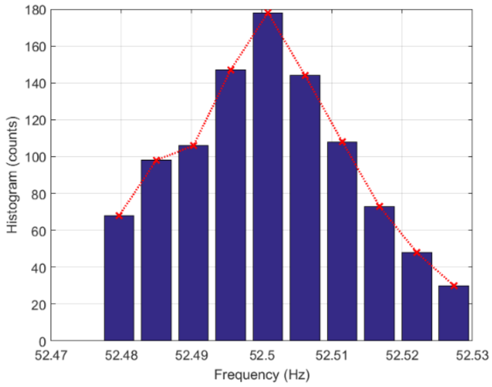
Sinewave and interharmonics frequencies	UC BK1823A		DMM Keysight 34465A	
	$\|FE\|_{\max}$ (mHz)	$\|RFE\|_{\max}$ (Hz/s)	$\|FE\|_{\max}$ (mHz)	$\|RFE\|_{\max}$ (Hz/s)
47.5 Hz & 25 Hz	8.60	0.06	64.00	0.83
52.5 Hz & 75 Hz	33.30	0.20	30.00	0.31

By filtering the accuracy of the frequency and *ROCOF* measurements achieved by both BK1823A and Keysight 34465A increases very much. In most situations the smallest errors are achieved by using BK1823A.

In Fig. 2 it can be seen that about half of the frequency measurements achieved by both instruments are very close to 52.5 Hz. Also, it is worth noticing that in the case of the BK1823A more different frequency values are achieved as compared with the case of a pure sinewave (see Fig. 1(a)).



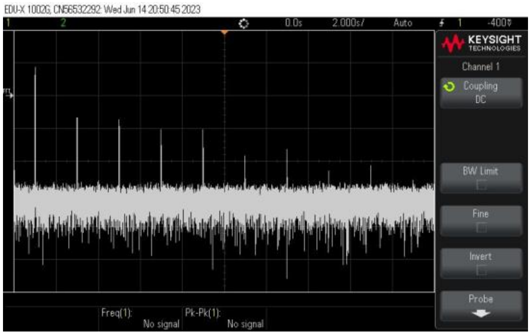
(a)



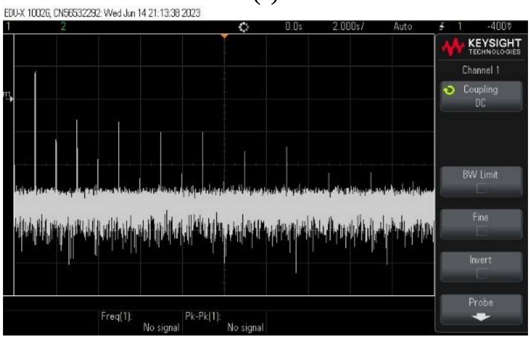
(b)

Fig. 2. Histograms of the frequency measurements achieved by the BK1823A (a) and the Keysight 34465A (b) when $GT = 0.1$ s in the case of a sinewave of frequency $f = 52.5$ Hz affected by an interharmonic of 75 Hz frequency, applied to a six-order band-pass filter. Amplitude of interharmonic equal to 10% of that of the fundamental component, $M = 1000$ measurements.

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. Fig. 3 shows the spectra of the power signals obtained when the hair dryer is off (Fig. 3(a)) and on (Fig. 3(b)). In Fig. 3 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 Tables 5 and 6. From Table 5 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.



(a)



(b)

Fig. 3. Spectra of the real-life power system signals obtained when a hair dryer is off (a) and on (b).

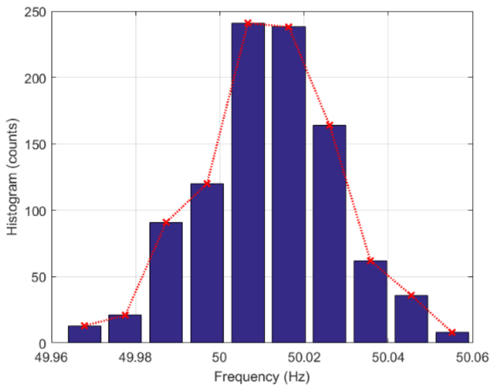
Table 5. Statistical results of the frequency measurements achieved by both instruments when GT = 0.01 s in the case of real-life power system signals obtained when a hair dryer is on.

Parameter	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

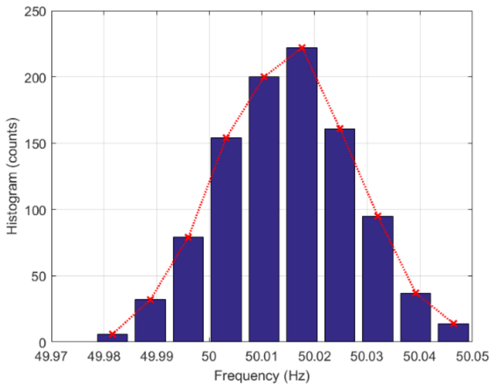
Table 6. Statistical results of the ROCOF measurements achieved by both instruments when GT = 0.01 s in the case of real-life power system signals obtained when a hair dryer is on.

Parameter	UC BK1823A	DMM Keysight 34465A
Minimum (Hz/s)	-0.26	-0.81
Maximum (Hz/s)	0.26	0.70
Mean (Hz/s)	-6.56E-5	-4.30E-3
Std. dev. (Hz/s)	0.08	0.81

Figs. 4 and 5 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)

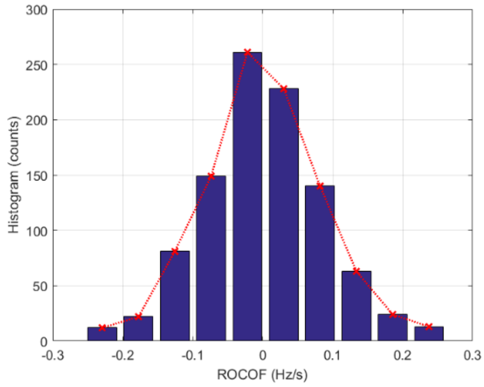


(b)

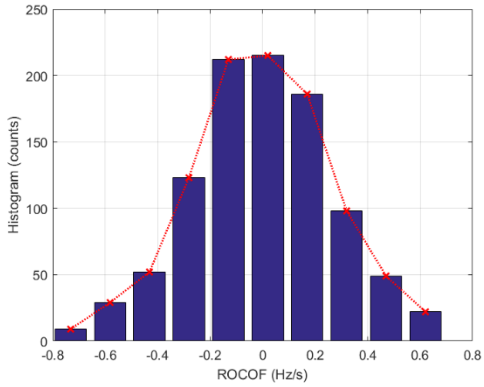
Fig. 4. Histograms of the frequency measurements achieved by the BK1823A (a) and the Keysight 34465A (b) when GT = 0.01 s in the case of real-life power system signals obtained when a hair dryer is on. M = 1000 measurements.

III. 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 conditions in the case of synthetized and real-life power system signals. 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 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 interharmonics. To avoid the contribution of the interharmonics on the frequency and *ROCOF* measurements the *GT* should be increased, and the analyzed signal should be filtered.



(a)



(b)

Fig. 5. Histograms of the *ROCOF* measurements achieved by the BK1823A (a) and the Keysight 34465A (b) when GT = 0.01 s in the case of real-life power system signals obtained when a hair dryer is on. M = 1000 measurements.

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