Influence of the DC offset on the DFT-based frequency estimation for noised multifrequency signals in PV systems with a DSP processor

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Abstract. Digital signal processing is present in many areas of industry and science. One of them is analyzing multifrequency signals, e.g. in photovoltaic systems. This paper focuses on the frequency estimation of pure signals and signals distorted by AWGN noise in the presence of a DC voltage offset. The used IpDFT estimation method is based on the FFT procedure, I class Rife-Vincent time windows and three points of the spectrum taken to calculations. Measurement time was limited only up to two cycles of a tested signal and the method is very accurate even below one cycle. Obtained results show that additional DC component negatively affect the accuracy. The paper can be very useful because it shows properties of the method in real measurement conditions for various values of parameters.

1 Introduction

Signal processing is a key part of many industrial and scientific applications. One of them is analyzing a multifrequency signal which consists of many sinusoidal components. Such signals occur as mechanical vibrations, telecommunication signals (e.g. passive intermodulation issue), radar signals, the grid signal, etc. [1 – 4]. Often, determining parameters is crucial for the whole measurement or power system. Nowadays, renewable energy systems are very popular and the estimation of grid frequency is often necessary to produce energy. Moreover, the faster and more accurate the method the better performance of the system. Using solar energy in photovoltaic systems is one of the most popular way to produce so called green energy [5]. The basic configuration here includes photovoltaic panels, the DC/DC converter, the DC/AC inverter and the control unit with a DSP (Digital Signal Processor) processor (Fig. 1). The value of frequency is obtained and used e.g. to drive the inverter, in the FLL (Frequency Locked Loop) algorithm, etc.

Several factors affect the energy quality in the grid and one of them is the DC voltage offset which emerges in some cases and its value depends on the application [6 – 10]. Main factors of this situation in the grid are e.g. offsets in voltage sensors, A/D converters, switching devices like power converters and lack of transformers to separate power systems. Usually, it is not a desired component in the signal because it distorts the waveform and causes e.g. saturation of transformers, generation of even harmonic, heating power receiving devices, etc. In the grid signal it is usually up to 0.1% of the amplitude values [6].

Nowadays, there can be found many various signal processing techniques to estimate the frequency. It is worth to note such methods like: subspace methods, Prony's methods, parametric modeling methods or DFT-based methods [11 – 13]. Methods based on the DFT spectrum are very fast but with not the highest accuracy. Some ways to improve it are: linear interpolation of DFT LIDFT [14] or spectrum interpolation methods (IpDFT) where several points of the spectrum are taken into calculations [15]. If these points have their weights methods are called MWIDFT (Multipoint Weighted Interpolation DFT). Other than DFT-based methods are usually very accurate but much slower which can cause problems in real time applications [16].

This paper presents estimation results of a newly developed IpDFT method that is applied for the grid signal frequency estimation in photovoltaic systems. Due to some international standards the maximum reaction time of the system is 2.5 cycle [17] (50 ms for 50 Hz signal). In this paper, the estimation time is limited up to 2 cycles to spare time for other algorithms implemented in the DSP processor. In this method, the Fast Fourier procedure to obtain the spectrum is used and also the 3-point interpolation and I class time windows are the base here. The tested signal was pure or with additional AWGN (Additive White Gaussian Noise) noise sinusoid with the DC voltage offset. Obtained results show properties of the method in real measurement conditions and for a short measurement time.

Section 2 gives some information about the estimation method and the signal processing in the photovoltaic system. Section 3 contains simulation results and conclusions are presented in Section 4.

2 Estimation method

The presented method was developed to estimate values of frequency in the model of the multifrequency signal:

$$x(t) = \sum_{i=1}^{M} A_i \sin\left(2\pi f_i t + \varphi_i\right) \qquad (1)$$

where: A_i – the amplitude of the i-th component, f_i – the frequency of the i-th component, φ_i – the phase of the i-th component, M – the number of sinusoidal components.

Time windows of H-order used for the method are I class Rife-Vincent windows which belong to the cosine windows family defined as [18 – 20]:

$$w_n = \sum_{h=0}^{H-1} (-1)^h a_h \cos\left(\frac{2\pi nh}{N}\right), \qquad n = 0, \ ..., \ N-1 \quad (2)$$

The spectrum for these windows can be approximated for $H > 1$, $N \gg 1$ and $N \gg \lambda$ as [20]:

$$W(\lambda) = \frac{D(\lambda)}{P(\lambda)} \qquad (3)$$

where

$$D(\lambda) = \frac{N(2H-2)!}{\pi 2^{2H-2}} \sin(\pi\lambda) e^{-j\pi\lambda} \qquad (4)$$

$$P(\lambda) = \lambda \prod_{h=1}^{H-1} \left(h^2 - \lambda^2\right) = \frac{\prod_{h=0}^{H} \left(h^2 - \lambda^2\right)}{(-\lambda)(H-\lambda)(H+\lambda)} \quad (5)$$

and $\lambda = fNT$ is a normalized frequency respect to the measurement time NT, where N is the number of samples in a measurement window and T is the sampling period. This value means also the number of signal cycles in the time window taken into calculations – CiR (*Cycle in Range*). According to IEC 61727 norm the length of the measurement window is up to 2 cycles in this paper [17].

The signal processing of the grid signal contains a few steps (Fig. 1). Firstly, the analog signal has to be sampled in the time window using an A/D converter. Later, samples are taken for the FFT procedure to obtain the signal spectrum. After that, an equation to obtain the value of frequency is used:

$$\hat{\lambda}_1 = \mathrm{Re}\left\{ \sqrt{\frac{\Pi_1}{\Pi_2}} \right\} \qquad (6)$$

where

$$\Pi_1 = \begin{vmatrix} (2H-1)H & (2H-1) & X_{k-1} - X_k \\ -k^2 - H^2 & 2k & X_k \\ (2H-1)H & -(2H-1) & X_{k+1} - X_k \end{vmatrix} \quad (7)$$

$$\Pi_2 = \begin{vmatrix} 1 & -(2H-1) & X_{k-1} \\ 1 & 0 & X_k \\ 1 & (2H-1) & X_{k+1} \end{vmatrix} = (2H-1) \begin{vmatrix} 1 & X_{k-1} - X_k \\ -1 & X_{k+1} - X_k \end{vmatrix} (8)$$

where $X(\lambda)$ are spectrum points for $\lambda = k - 1$, k, $k + 1$ (values X_{k-1}, X_k, X_{k+1}) around the main lobe.
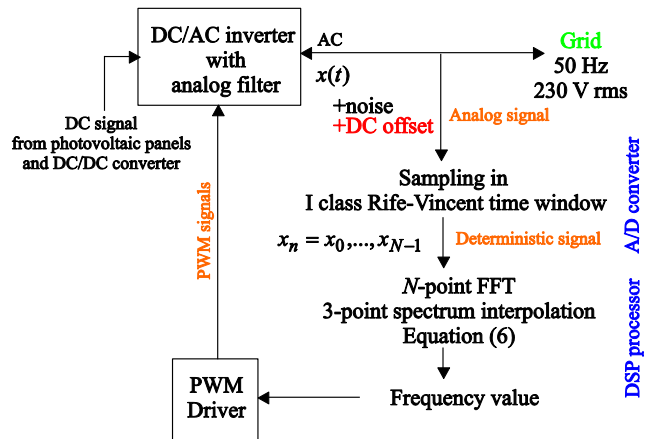

Fig. 1. Grid signal processing to obtain the frequency value in the control of the photovoltaic system.

3 Simulation research

Presented in this paper simulation results were obtained in the MATLAB environment. Estimation errors were determined as maximum errors of the entire range of φ_1 (0 – 2π in steps of 0.01 rad) for each CiR value. In the first part a pure grid signal was tested (without disturbances) with additional DC voltage offset (marked as DC in figures) up to 0.1% according to [6]. The second part contains results for the signal with added AWGN noise and also with the DC component.

Systematic errors for the signal without the offset decrease when number of N, H increases (errors are inversely proportional to N^{2H}) (Fig. 2, Fig. 4). Also, in the tested range of $CiR < 2$ the most accurate results are obtained for $k = 1$. After adding the 0.1% dc voltage offset the accuracy is changing because the offset distorts the spectrum and the method uses three initial samples of the spectrum due to very short measurement time. For $H = 2$ the most accurate results are obtained for $k = 3$ which means that among the three point of the spectrum taken into calculations there is not the point from the zero frequency where the offset occurs and that the spectrum distortion has smaller effect on results (in Fig. 2 curves for $H = 2$ are the same for the signal with the offset and without it). When the H increases, the accuracy is worse because of the wider main lobe of the time window in the spectrum domain and hence the spectrum is longer distorted by the offset (while increasing the CiR) and the DC has bigger effect on results. In this situation, to increase the accuracy CiR should be much longer than 2 (but then the time limit for photovoltaic systems is exceeded) or k should be much bigger than 1 (at least 8 for $H = 7$). Of course, the bigger value of the DC offset the least accurate the results (Fig. 3). Bigger number of samples N in this case does not improve the accuracy (Fig. 4) and it is approximately 10^{-4} Hz/Hz for 512 samples in the measurement window, $CiR = 0.5$, $k = 2$ and DC = 0.02%.

In the second part of simulations the *eMSE* (*empirical Mean Square Error*) error was calculated as the estimation error defined in [21]. Results were compared to the Cramér-Rao (*CRB*) bound (Fig. 5) for various number of H, DC and k as a function of *SNR*

(*Signal to Noise Ratio*). The bigger *SNR* the more accurate the method for the signal without the DC offset or for $k = 3$. However, in the presence of the DC curves for $k = 1, 2$ are on the constant level from some *SNR* value. In this case, the systematic error of the method (for the signal without noise) is bigger than the error caused by the AWGN noise. So for example, for $k = 2$, $H = 7$ and DC = 0.1% increasing the *SNR* value (the noise has lower power) does not improve the accuracy from about 60 dB. Also, the bigger H value the less accurate results.
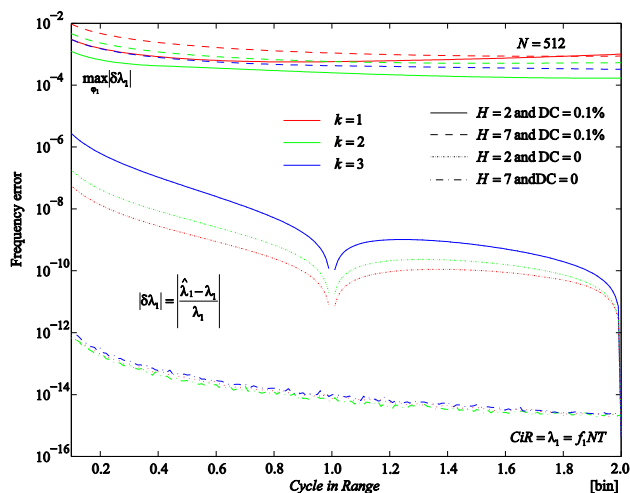

Fig. 2. The frequency estimation for the different number of k, H and DC as a function of *CiR*.
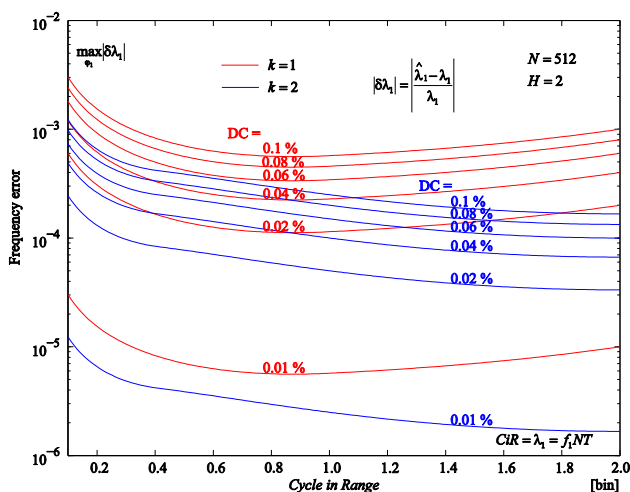

Fig. 3. The frequency estimation for the different number of k for the non-zero DC component.
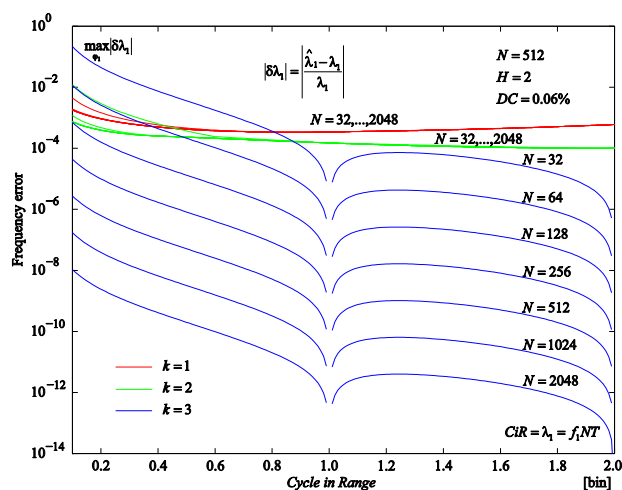

Fig. 4. The frequency estimation for the different number of k and samples N in the measurement window.
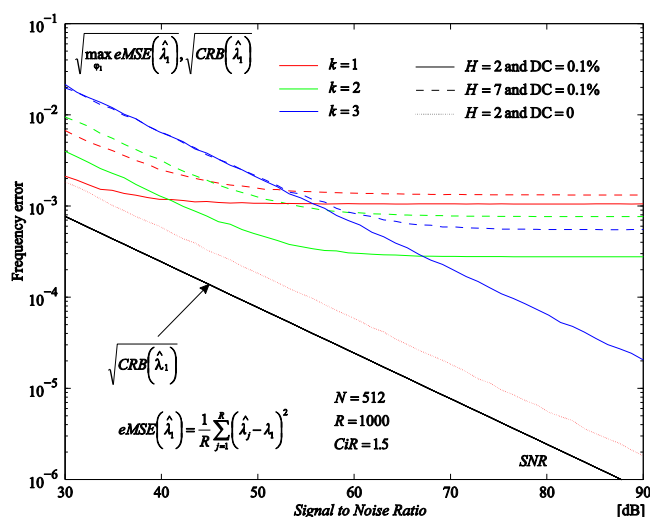

Fig. 5. Statistical properties of the method in the presence of the DC voltage offset.

3 Conclusions

This paper presents simulation results of a DFT-based estimation method of multifrequency signals in various measurement conditions with additional DC voltage offsets for the short measurement time up to 2 cycles.

The method without the DC offset is very accurate and very fast (even below one period of the tested signal) in various measurement conditions. However, the additional DC component in the signal causes bigger estimation errors and it is necessary to extend the measurement time or increase the index k in the (6) to improve the accuracy. Also, a very good option is filtering the signal before the estimation process to reject the DC component from the spectrum.

Obtained results show the accuracy in various measurement conditions in the presence of the DC offset in the signal which usually takes place in practice. Further research will be focused on the elimination of this component using digital filters with a short group

delay which is important to fulfill maximum time conditions in photovoltaic systems.

Acknowledgement

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