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Assessment of Power Frequency Estimation Methods in Distributed Generation in Islanding Condition

***Abstract**. In this paper, a method for evaluation of power frequency estimation during transient operation in distributed generation (DG) in islanding conditions is presented. For this end, five methods of fundamental frequency estimation are evaluated in a distribution system with distributed generation in islanding operation, such as: (a) zero crossing, (b) adjustment of points to a pure sinusoidal waveform, (c) hybrid method, (d) discrete Fourier transform method based, and (e) Prony-Fourier-based algorithm. The estimators are compared and evaluated in two different ways, using two analytical functions, and in an electric power distributed system with DG in islanding condition. The evaluation methodology for the frequency estimators are based in statistical errors, taking into account mean, mean square error. The zero-crossing and discrete Fourier transform based estimator presented better results in comparison with the other evaluated algorithms. However, the discrete Fourier transform presented good results in the estimated frequency in the three evaluated cases.*

***Streszczenie.** W artykule oceniono metody badania częstotliwości w stanach przejściowych rozproszonych sieci energetycznych w warunkach tworzenia się wysp. Zbadano pięć metod: zero crossing, APPSW, hybrydową, DFT iProny. Najlepszy wyniki osiągnięto przy stosowaniu metody zero-crossing (Przeciecia osi zero) I DFT. **Ocena metod określania częstotliwości w stanach przejściowych rozproszonych sieci energetycznych w warunkach tworzenia się wysp**.*

Keywords: Frequency estimation, fundamental frequency, distributed generation, islanding condition, protection.
Słowa kluczowe: określanie częstotliwości, rozproszone sieci energetyczne, powstawanie wysp

Introduction

The power system frequency has an important role in order to perform monitoring and controlling the power quality in electrical distribution systems with distributed generation (DG). However, in electrical systems with high penetration of DG changes occurs such as the unintentional islanding of DG for example. Islanding situations can occur with the disconnection of DG during the normal operation, then, the frequency, changes suffer from the high load disconnection of the system that can affect the safety and reliability of the islanded area.

For this reason, many algorithms are presented for fundamental frequency estimation applied in electric power systems, such as: zero-crossing method [1, 3], adjustment of points to a pure sinusoidal waveform (APPSW) [1], hybrid method [4, 5], discrete Fourier transform method (DFT) [2, 6], Prony-Fourier-based algorithm [7, 8], and other methodologies such as: Kalman filtering [10], least mean square (LMS) [11].

To solve the problem of islanding detection, schemes are used to detect an islanding operation of DG. Different methods for islanding detection have been reported in recent years [14, 15]. Islanding detection techniques are usually divided into: (a) local detection methods when the detection is based on the DG side, and (b) remote detection methods when the detection is based on the network side. Local detection methods can be passive methods or active methods [16].

The passive methods monitor voltages and currents waveforms. Voltage, frequency, harmonic and phase measurements are taken separately or simultaneously to determine an islanding situation. Frequency-based schemes [15, 16] as frequency relay [14–16], rate of change of frequency (ROCOF) relay [17, 18] were studied to islanding detection. However, in the aforementioned papers, the transient state is not taken in account in the frequency estimation. The transient state affects the frequency estimation quality. In transient state, frequency estimation is used by protection and metering. With the connection of DG, the effect of the transient regime in frequency estimation is higher. Besides, the methods [1,2,4,5,7,8], were not applied in DG. Therefore, a method for the evaluation of the quality of the frequency estimation in power systems with DG is needed.

In this paper a method for evaluation of the quality frequency estimation taking into account the influence of islanding condition of DG is present. Therefore, the zero crossing frequency estimation, APPSW, hybrid method, DFT, and Prony-Fourier-based algorithm are evaluated in two simulation scenarios, such as analytical signals and in a distribution system test with DG. Mean square error (MSE) method was applied to performance analysis of algorithms. An EMTP program known as Matlab®/Simulink for evaluate and simulations was used. The DFT method obtained best results for frequency estimation for islanding detection in comparison with the other algorithms.

Description of methods applied for frequency estimation

The description of five methods applied for fundamental frequency estimation is presented in this section.

Method based on signal zero-crossings

The signal algorithm is based on the measurement of the time interval between two zero-crossings of the sampled signal. The exact time of the zero-crossing is obtained by linear interpolation between two consecutive samples of different sign [1] is given by:

$$t_{zc} = \frac{t_{k-1}V_k - t_k V_{k-1}}{V_k - V_{k-1}}, \tag{1}$$

where (k) denotes the sample that follows the zero crossing, (k−1) denotes the sample before the zero crossing, (Vk,Vk−1) and (tk, tk−1) are the voltage and time of the samples (k) and (k−1), respectively.

During the time interval between two zero-crossings, the frequency value is assumed to be equal to the last calculated value. The frequency in the instant (k) is calculated by:

$$f_k = \frac{1}{2 * (t_{zcnext} - t_{zcprevious})}, \tag{2}$$

where f_k denotes the fundamental frequency, in Hz, calculated in the sample *k* by zero-crossing, t_{zcnext} denotes the time of the next zero-crossing, $t_{zcprevious}$ denotes the time of the previous zero-crossing.

Adjustment of points to a pure sinusoidal waveform method

This method was applied in [1] and it use trigonometric relations to find the frequency value. A method based on three consecutive samples (V_{k-2}, V_{k-1}, V_k), spaced by a time interval Δt was used. In such conditions, the pure sinusoidal wave fulfils the following relationship:

$$\cos(2\pi f \triangle t) = \frac{V_{k-2} + V_k}{2V_{k-1}}. \tag{3}$$

The frequency *f* is obtained as from the calculated voltage at sample (*k*) and the time interval Δt given by:

$$f_k = \cos^{-1}\left(\frac{V_{k-2} + V_k}{2V_{k-1}}\right)\frac{1}{2\pi\triangle t}. \tag{4}$$

Combined frequency estimation technique: hybrid method

This method was presented by [4] and combines two traditional techniques. The method combines the zero-crossings method and the APPSW method, if T_2 is the time length of the latest three cycles. The precision of the zero-crossings is corrupted by effect of noise and harmonics. To minimize this problem, an average of the frequencies of the last three cycles of the signal can be used, given by:

$$f_2 = \frac{3}{T_2}. \tag{5}$$

The equation (5) provides greater immunity to signal distortions. However, this method is less sensitive to frequency variations. For this reason, f_1 (frequency obtained by zero-crossing in one cycle) or f_2 (frequency obtained by zero-crossing in three cycles) are used, given by:

$$\begin{aligned} &If|f_2 - f_1| < Th_1,\\ &then : f_0 = f_2,\\ &else : f_0 = f_1, \end{aligned} \tag{6}$$

where f_0 denotes the final value estimated by the sample count and interpolate method, T_{h1} denotes a threshold value equal to the maximum error due to noise and harmonic effects in (5). The value used for T_{h1} is 0.001 Hz [4].

The second method APPSW has the same problem that the zero-crossing. The specified conditions are as follows:

$$If\left|\frac{fr_{k-1} + fr_{k-2} + fr_{k-3}}{3} - fr_k\right| < Th_2,$$

$$then : f_k = fr_k, \tag{7}$$

$$else : f_k = f_{0k}, \tag{8}$$

where: (*k*) represents the sample number, f_{rk} denotes the value of frequency estimated by the APPSW algorithm, f_{0k} denotes the value of frequency estimated by the zero-crossing algorithm, and f_k denotes the final output of the frequency estimation algorithm. Results obtained from simulation studies indicate that an appropriate value for Th_2 is 0.05 Hz [4].

Method based on discrete Fourier transform

This method is based on DFT. This technique measures the angular velocity of the voltage phasors [6]. The voltage phasor of the fundamental waveform can be calculated from the N samples. The DFT is applied to a N length data window equal to the number of samples per cycle of the nominal frequency of the system. If the sampling windows equal one cycle of the basic waveform, the phasor on the sample (*k*) at the time $t_k = kT$ is given by:

$$G_k = \frac{2}{N}\sum_{n=0}^{N-1} v_M e^{j\omega T n}, \tag{9}$$

where

$$M = k + n - N + 1,$$

and T denotes the sampling interval, ω denotes the fundamental angular frequency, and v_M is the sampled values of voltage.

The value of G_k is updated at every sampled value. After each sampling cycle, the newest sample is taken into the calculation, while the oldest one is neglected. For each position of the phasor, its argument can be calculated. The instantaneous angular frequency can be determined from the two consecutive phasors:

$$f_k = \frac{arg[G_{k+1}] - arg[G_k]}{2\pi T}, \tag{10}$$

$$arg[G_k] = \tan^{-1}\left\{\frac{Im[G_k]}{Re[G_k]}\right\}, \tag{11}$$

where $\omega = 2\pi f$.

Prony-Fourier-based algorithm

This method filters the voltage fundamental component by DFT [8] as follows:

$$g_k = \frac{2}{N}\sum_{n=0}^{N-1} v_{k+n-N+1}\cos(n\omega T). \tag{12}$$

However, when the frequency changes, the rectangular window inherent in the DFT has some disadvantages [**8**]. A smoothing window called Hamming window is applied to improve the filter properties.

The Hamming window presented in Fig.1 is described by:

$$w_H = 0.54 - 0.46\cos\left(\frac{2\pi n}{N-1}\right). \tag{13}$$

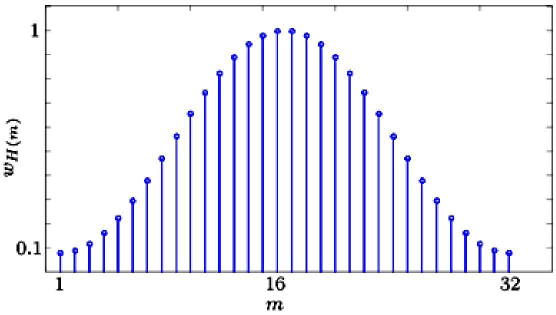

Fig. 1. Digital filter: samples for Hamming window, m = 32

Apply the Hamming window:

$$g_k = \left(\frac{2}{N} \sum_{n=0}^{N-1} v_{k+n-N+1} \cos(n\omega T) \right) w_{H(N)}. \quad (14)$$

The aim of the window is to improve the accuracy of the frequency determination. The voltage filters presented in (14) are used to determinate the frequency by:

$$f_k = \frac{1}{2\pi T} \cos^{-1} \left\{ \frac{\sum_{k=2}^{M-1} (g_{k-1} + g_{k+1})^2}{2 \sum_{k=2}^{M-1} g_k (g_{k-1} + g_{k+1})} \right\}, \quad (15)$$

where N denotes the number of samples per cycle, M was adjusted to 15 .

Methodology applied for frequency estimation

The methodology applied in this paper for fundamental frequency estimation in electric power system consist in three stages presented in Fig. 2.

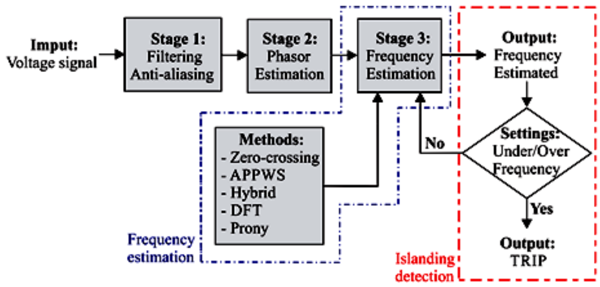

Fig. 2. Flowchart of the methodology for frequency estimation and islanding detection

Stage 1

In this stage, voltage signals were filtered. In order to eliminate all harmonic components. An analog third-order Butterworth anti-aliasing filter with a cutoff frequency of 180 Hz is used on a slide window with 20 kHz sampling frequency.

Stage 2

Fourier algorithms were used for the phasor estimation (module and phase) of the fundamental components of the tested periodic signals. The Full Cycle Discrete Fourier Transform - FCDFT was used. Windows with a period T_0 of the periodical signal $x(t)$ on the fundamental frequency were used. The methodology for phasor estimation provides real and imaginary values of the phasor as follows:

$$X_{re} = \frac{2}{T_0} \int_{t_0}^{t_0+T_0} x(t) \cos(2\pi f_0 t)\, dt, \quad (16)$$

$$X_{im} = \frac{2}{T_0} \int_{t_0}^{t_0+T_0} x(t) \sin(2\pi f_0 t)\, dt. \quad (17)$$

Considering a window with N samples per cycle. In this way, the real X_{re} and imaginary X_{im} part of the signal $x(t)$ are given by:

$$X_{re}(k) = \frac{2}{N} \sum_{n=k}^{k-N+1} x_n \cos\left(\frac{2\pi}{N} n\right), \quad (18)$$

$$X_{im}(k) = \frac{2}{N} \sum_{n=k}^{k-N+1} x_k \sin\left(\frac{2\pi}{N} n\right). \quad (19)$$

Stage 3

In this stage, five methodologies for fundamental frequency estimation were applied: (2) method based on signal zero-crossings [1], (4) APPSW method [1], (5), (6), (7), hybrid method [4], (10), (11) method based on discrete Fourier transform [7], and (15) Prony-Fourier-based algorithm [7].

Performance Assessment

The frequency estimators are tested in 2 different functions cases, such as:

- Case 1: fundamental signal with harmonic and one DC exponential decay;
- Case 2: fundamental signal with harmonic and two DC exponential decay.

In addition, the estimators are compared and evaluated in the electric power distribution system with distributed generation in islanding condition.

Analytic signals

The two analytic signals [21] applied for test are:

- Fundamental signal with harmonic and one DC exponential decay,
- Fundamental signal with harmonic and two DC exponential decay,

Case 1: Fundamental signal with harmonic and one DC exponential decay

The signal applied with a time constant τ was modeled by:

(20)

$$f_1(t) = \left[\sum_{n=1}^{30} \frac{50}{n} \cos(n\omega t + n\alpha) \right] - 50 \cos(\alpha). \exp^{-\frac{t}{\tau}}.$$

This signal is presented in Fig. 3. In (a), the signal is obtained with a constant time τ = *0.5 cycles* and *5 cycles*, and with an angle of voltage $\alpha = 45^o$.

The fundamental frequency estimated by function (20) are presented in Fig. 3 (b), (c), (d), (e), and (f).

Case 2: Fundamental signal with harmonic and two DC exponential decay

The signal applied with a time constant τ and the constant secondary time τ_s was modeled by:

$$f_1(t) = \left[\sum_{n=1}^{30} \frac{50}{n} \cos(n\omega t + n\alpha) \right] - 55 \cos(\alpha). \exp^{-\frac{t}{\tau}} + 5 \cos(\alpha). \exp^{-\frac{t}{\tau_s}}. \quad (21)$$

This signal is presented in Fig. 4 (a), the signal is obtained with a constant time τ = *0.5* cycles and 5 cycles, and the constant secondary time τ_s = *20* cycles, with an angle of voltage $\alpha = 45^o$.

In Fig. 3 and 4, the methods zero-crossing and DFT presented the best results for frequency estimation. The Prony method presented the worst solution in comparison with the other evaluated methods. However, the zero-crossing obtained best result because this method is not affected by the harmonic and DC component.

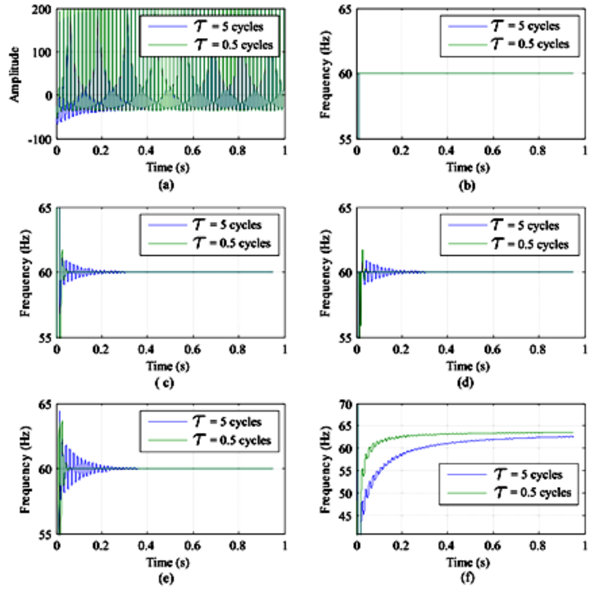

Fig. 3. Signals obtained from test function: (a) signal with harmonic and one DC exponential decay with α = 45°, Fundamental frequency estimated by: (b) Zero-crossing method, (c) APPSW method, (d) Hybrid method, (e) DFT method and (f) Prony method.

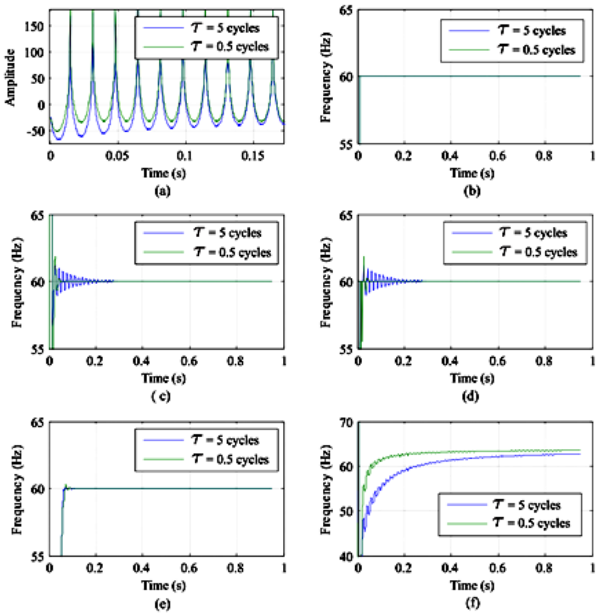

Fig. 3. Signals obtained from test function: (a) signal with harmonic and one DC exponential decay with α = 45°, Fundamental frequency estimated by: (b) Zero-crossing method, (c) APPSW method, (d) Hybrid method, (e) DFT method and (f) Prony method.

Electric power distribution system test

The test power system used presented in Fig. 5 [20] is a 132 kV transmission line Thevenin equivalent connected to a transformer 132/33 kV in delta/wye-ground. The 33 kV distribution system is composed by 5 equivalent RL branches, Table 1, with 7 buses. This distribution system is connected to a synchronous generator of 30 MVA, DG, by a transformer 33/6.9 kV in delta/wye-ground.

In this paper, all network components were represented by three-phase models. Distribution feeders were modeled as series RL impedances, and transformers were modeled using the T circuit [20]. Synchronous generators were represented by a sixth-order three-phase model in the rotor reference frame. The generators were equipped with an automatic voltage regulator represented by the IEEE type 1 model [22].

Table 1. Line data, values in Ω

	Line 1	Line 2	Line 3	Line 4	Line 5
R	0.5624	0.4999	0.3124	0.2499	0.1875
X	2.5318	2.2505	1.4066	1.1252	0.8439

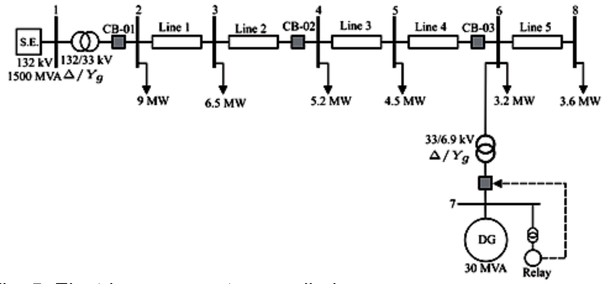

Fig. 5. Electric power system applied

For the algorithms evaluation, islanding conditions for DG were simulated. The islanding situation is simulated by opening the circuit breaker CB installed at bus 2 at *t*=8s, which remains open until the end of the simulation at *t*=10s. The frequency estimation is measuring the parameters in the bus near the DG. The power imbalance of the islanded system is gradually varied from 0 to 1 p.u., referred to the MVA rating of the generator.

The simulation results presented were all processed using Matlab®. The sampling frequency was set to 20 kHz in 60 Hz systems. The simulated data were pre-conditioned using a third-order Butterworth low-pass filter with a cutoff frequency of 180 Hz in order to reject high-frequency components and prevent aliasing errors.

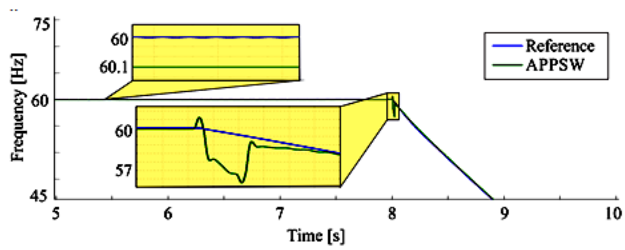

Fig. 6. Fundamental frequency estimated by APPSW method for DG = 15 MVA.

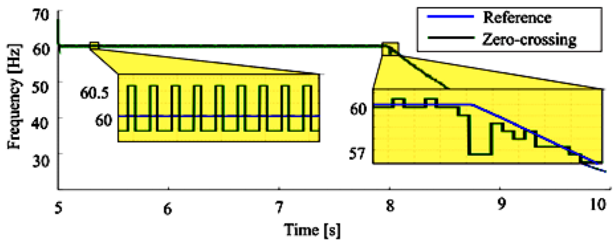

Fig. 7. Fundamental frequency estimated by Zero-crossing method for DG = 15 MVA.

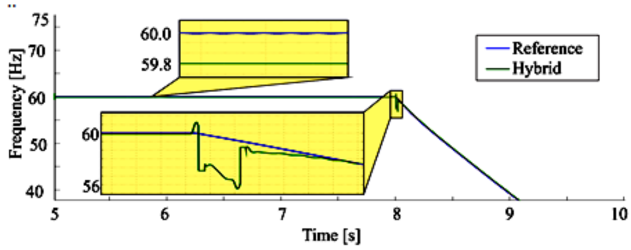

Fig. 8. Fundamental frequency estimated by Hybrid method for DG = 15 MVA.

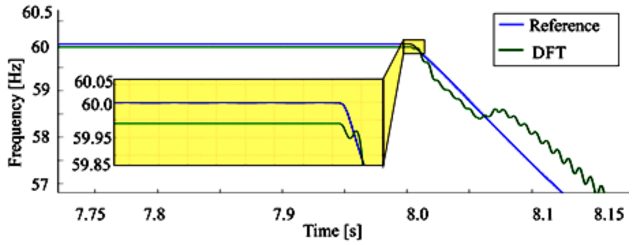

Fig. 9. Fundamental frequency estimated by DFT method for DG = 15 MVA.

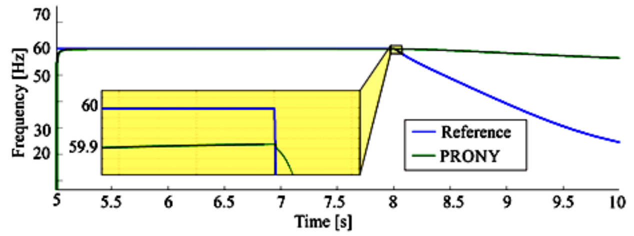

Fig. 10. Fundamental frequency estimated by Prony method for DG = 15 MVA.

Fig. 6, 7, 8, 9, and 10 depicts the performance of the frequency estimation-based algorithms (APPSW, Zero-crossing, Hybrid method, DFT, and Prony method). The Zero-crossing have a poor convergence during the simulation presenting oscillation due to the sampling rate. However, poor convergence after da islanding event the Prony method presented.

For frequency estimation, the algorithm performance can be well assessed by square error indices (MSE), Fig. 11. Due to its greater independence from the size of the analyzed interval.

$$MSE = \frac{\sum_{i=1}^{n}(y_{real} - y_{estimated})^2}{n},$$

(22) $$MSE = \frac{\sum_{i=1}^{n}(er(i))^2}{n}.$$

where, y_{real} and $y_{estimated}$ are the real and estimated value estimated for the method, n is the total samples of the simulation, *er* is the absolute error of the estimation value.

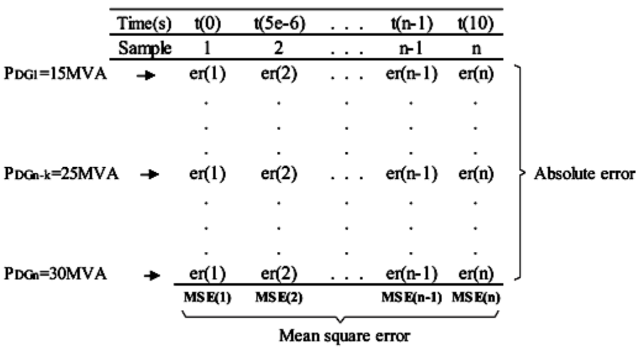

Fig. 11. Explicative method for calculation of the mean square errors for the fundamental frequency estimation.

The estimation errors are presented in Fig. 12 and 13. This figure present the behavior of the error calculated before and after the islanding situation.

Table 2 presents the errors for the estimation of fundamental frequency for the implemented methods before and after islanding situation (i.e., islanding situation in t=8s.

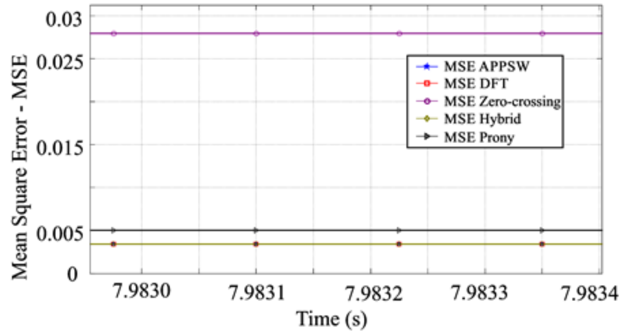

Fig. 12. Mean square error of the methods applied. Signal before the islanding situation.

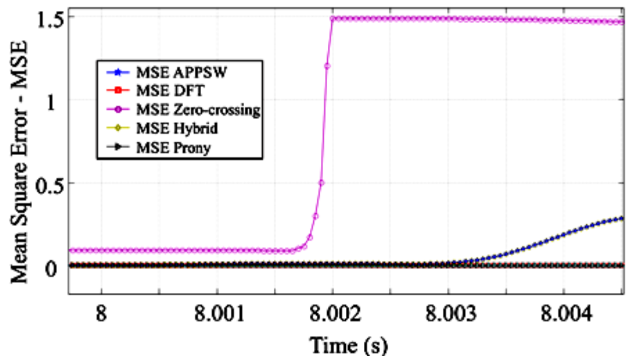

Fig. 12. Mean square error of the methods applied. Signal after the islanding situation.

Table. 2. Mean square error of the methods of fundamental frequency estimation.

Time (s)	Zero-crossing	APPSW	Hybrid	DFT	PRONY
7.97	0.0308	0.0034	0.0034	0.0034	0.0050
7.98	0.0280	0.0035	0.0035	0.0035	0.0050
7.99	0.0280	0.0034	0.0034	0.0034	0.0050
8.00	0.0932	0.0034	0.0034	0.0034	0.0050
8.01	1.2904	0.8637	0.8637	0.0009	0.0011
8.02	0.0812	1.8802	1.8802	0.0204	0.0264
8.03	0.0805	0.0409	0.0409	0.0280	0.0909

After the islanding situation t=8s the signals present oscillations by the disconnection of the principal power supply of the system and evaluated methods present an increase in estimation error. However, the method DFT presents a best result in comparison with the other evaluated methods as shown in the Table 2.

Conclusion

The paper describes the evaluation of five frequency estimation methods, such as: zero crossing, APPSW, hybrid method, discrete Fourier transform and Prony-Fourier-based algorithm applied for accurate and fast determination of the main fundamental frequency in two different function cases, such as: fundamental signal with harmonic and one DC exponential decay, a fundamental signal with harmonic and two DC exponential decay, and a power system with distributed generation in islanding condition. After anti-aliasing filtering, a phasor estimation is performed in the output signals with the full cycle Fourier algorithm. Finally, the frequency estimation with the evaluated methods is performed in the processed signals. The evaluated methods are found to be accurate and fast when estimating the fundamental frequency of the test signals, and the distributed generation signals in islanding condition. The zero-crossing method presented the best result on the frequency estimation in the two first evaluated cases. However, applied this method to the electric power system test the performance of zero-crossing was reduced in comparison with the DFT method that obtained good results on the three simulated cases. Results obtained from various simulation studies demonstrate the effectiveness of the DFT technique in comparison with the other evaluated methods. The DFT method provides good results, even for the signals contaminated with significant noise or harmonics. The DFT provides satisfactory performance and could be used in digital power system protection relays or in the digital protection of islanding detection of distributed generation systems.

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