7Evaluation of Frequency Estimation Algorithms Applied in System with Distributed Generation in Island Operation

Huilman S. Sanca, Benemar A. de Souza, Flavio B. Costa, and Francisco C. Souza Jr.

Abstract—This paper compares the performance of two algorithms for fundamental frequency measurement. Here, the performance of these algorithms will be evaluated during a transient situation generated by the disconnection of the distributed generation (DG) of the rest of the main distribution systems. This situation is known as islanding condition of the DG. These evaluated algorithms are based on techniques such as (a) method based on discrete Fourier Transform (DFT) and (b) Prony Fourier algorithm. The methodology for evaluation of performance was obtained by simulation of experimental cases of 32 kV distribution system in islanding condition. The islanding events were made varying the distributed synchronous generator nominal power. Here, the distribution system is connected to a synchronous generator of 30 MVA. Therefore, the performance of frequency estimation methods evaluated in islanding condition is based on statistical errors, relative error. The DFT-based estimator showed a better transient behavior in all the analyzed cases in comparison with the other evaluated algorithm.

Index Terms—Frequency estimation, DFT, performance, islanding condition, distribution system, distributed generation, synchronous generator.

1 Introduction

ACTUALLY, the distribution systems have changed with the connection of distributed generation (DG) [1]. Electric power systems are expected to raise in complexity as a result of the integration of DG systems [2], [3]. DG has grown over the years mainly due to environmental issues. DG are many varieties and sizes [4]. For it, the estimation of parameters such as amplitude, phase and frequency of a power signal has immense application in the areas of control and protection of power systems [5] and in the smart grid. With the increasing penetration of DG in the electrical distribution system and in efficient micro grid new series problems of control, protection and operation of the electrical system are created. For instance, one of the many problems is known as unintentional islanding. An islanding operation occurs when the DG continues supplying power to the network after power from the main utility is interrupted. After the islanding situation, the output voltage and current signals from the terminals of a DG system in a microgrid vary widely depending on the variation of the operating conditions of the system. To solve this problem, many methods for islanding detection have been studied. In power distribution system schemes to detect an islanding operation are used, and for this can be considered the international standards [6], [7]. Different methods for islanding detection have been reported in recent years [8], [9], [10], [11], [12].

Passive methods to monitor voltages, currents, phase and frequency were studied. However, these methods do not guarantee the performance for all load conditions [13]. Frequency-based schemes as frequency relay [14], rate of change of frequency (ROCOF) relay [12], rate of change of frequency over power [15] are some examples for passive method local detection. Thus, frequency measurement is an important parameter in power system operation as it indicates the dynamic balance between power generation and its utilization. Frequency is a fundamental parameter in power system analysis, operation, and control; hence, its fast and precise estimation is of prime importance [16].

In electric power systems, the frequency estimation and its parameters as the amplitude and the phase of the voltage or current signals are a very important issue to any application in microgrids or DG [3], [17].

Several methods have been employed for frequency estimation to name some: zero-crossing method [18], [19], adjustment of points to a pure sinusoidal waveform (APPSW) [20]. However, some techniques use balanced three phase signals for resolving zero-crossing issues, thus they cannot deal with unbalanced conditions, and other methodologies as: Kalman filtering [21]; least mean square (LMS) [22]; least error square [23]; Phase-locked loop (PLL) [24]; hybrid method [25], [26], discrete Fourier transform method (DFT) [27], [28], hybrid method [25], Prony-Fourier-based algorithm [29], [30]. All these methods for frequency estimation have been evaluated in the steady state of electric power

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system. However, In DG, island operations can occur and, to re-connect to the network, is necessary which the frequency be the same on both sides, otherwise, damage DG can happen. For this reason, frequency estimation algorithms have to be robust and reliable.

This paper compares the transient performance in islanding condition of DG of two algorithms for fundamental frequency measurement. The algorithms are based on techniques such as: (a) method based on discrete Fourier Transform (DFT), technique measures the angular velocity of the voltage phasors, based on DFT, and (b) Prony Fourier algorithm, which filters the fundamental component of voltage with a filter based in DFT. The performance comparison was made by the estimation of the fundamental frequency. In all cases, a frequency estimation method is implemented in the corresponding DG unit. The performance was obtained by simulation for voltage waveforms sampled in experimental cases of a distribution system in islanding condition of DG. The frequency estimators are compared and evaluated in the electric power distributed system with DG. The test power system used is a 132 kV transmission line Thevenin equivalent connected to a transformer 132/33 kV in delta/wye-ground, and the 33 kV distribution system is composed of 5 equivalent RL branches with 7 buses, this distribution system is connected to a synchronous generator of 30 MVA. The DG is connected by a transformer 33/6.9 kV in delta/wye-ground. The simulation of the distribution power system and the islanding events were made varying the nominal power of the distributed synchronous generator. Therefore, the frequency estimators were used to estimate the frequency for this islanding conditions. The evaluation methodology for the frequency estimators is based on statistical errors, relative error. The DFT based estimator presented better results in comparison with the other evaluated algorithms. The analysis of the effect of harmonic distortion in the voltage signal is out of the scope of this paper.

2 Description of the Frequency Estimation Algorithms

2.1 Algorithm Based on DFT

This technique measures the angular velocity of the voltage phasors [29]. The voltage phasor of the fundamental waveform can be calculated from the N samples. The DFT is applied to an N length data window equal to the number of samples per cycle of the nominal frequency of the system. If the sampling window equals one cycle of the basic waveform, the phasor on the instant (k) at the time $t_k = kT$ is given by:

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

where:

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

where, T denotes the sampling interval; ω denotes the fundamental angular frequency, and v_M 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 voltage phasors, where $\omega = 2\pi f$:

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

where

$$arg[G_k] = \tan^{-1}\left\{\frac{Im[G_k]}{Re[G_k]}\right\}. \tag{3}$$

2.2 Prony-Fourier-based Algorithm

This method filters the voltage fundamental component by DFT [29] is given by:

$$g_k = \frac{2}{N}\sum_{n=0}^{N-1} v_{k+n-N+1}\cos(n\omega T). \tag{4}$$

However, when the frequency changes, the rectangular window inherent in the DFT has some disadvantages [29]. To improve the filter properties, a smoothing window called Hamming window is applied.

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

$$w_H = 0.54 - 0.46\cos\left(\frac{2\pi n}{N-1}\right). \tag{5}$$

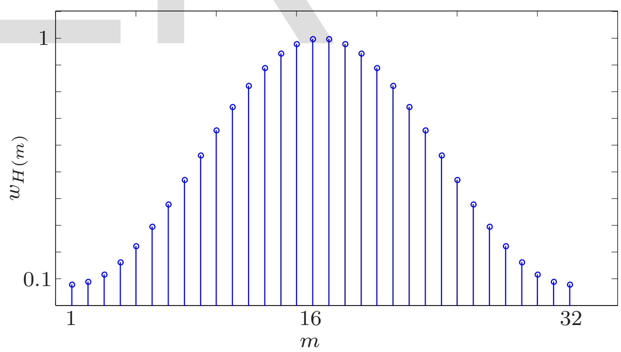

Fig. 1. Digital filter: Samples for Hamming window, $m = 32$.

The Hamming window is applied at (4) getting:

$$g_k = \left(\frac{2}{N}\sum_{n=0}^{N-1} v_{k+n-N+1}\cos(n\omega T)\right) \times w_{H(N)}. \tag{6}$$

The aim of the window is to improve the accuracy of the frequency determination. The voltage filters presented in (6) are used to determinate the frequency by:

$$f_k = \frac{1}{2\pi T}\cos^{-1}\left\{\frac{\sum_{k=2}^{M-1}\left(g_{k-1}+g_{k+1}\right)^2}{2\sum_{k=2}^{M-1} g_k\left(g_{k-1}+g_{k+1}\right)}\right\}, \tag{7}$$

where N denotes the number of samples per cycle, M was adjusted in 15 [29].

3 Methodology Applied for Frequency Estimation

3.1 Islanding of Distribution System with DG

Frequency measurement in DG is necessary to implement in order to know and maintain the active power balance. Frequency control is particularly important during the permanent and transient situation generated by transitions between grid-connected and islanding modes of DG, where high deviations of frequency can occur. Besides, frequency estimation is also needed for implement protection schemes based on frequency measurement. It is for this reason that the algorithms for frequency estimation have to be necessary evaluate for applying in anti-islanding protection schemes Fig.2.

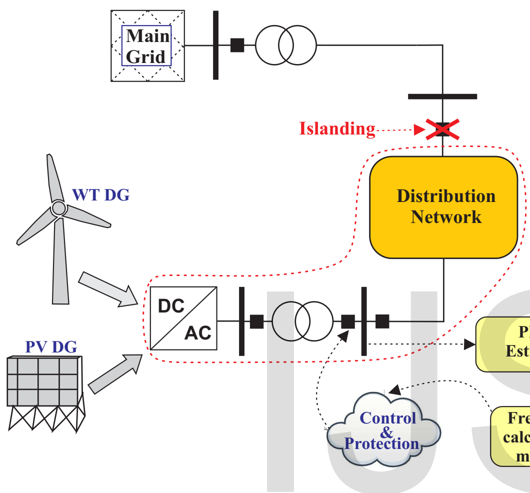

Fig. 2. Distributed generation system in islanding conditions scheme.

3.2 Steps of Methodology

3.2.1 Step 1

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.

3.2.2 Step 2

Fourier algorithms for the phasor estimation were used. The Fourier filter allows the extraction of module and phase of the fundamental components of the tested periodic signals. The digital Fourier filter used is the Full Cycle Discrete Fourier Transform - FCDFT. The methodology for phasor estimation provides real and imaginary values of the phasor. Considering a window with N samples per cycle and a period T_0. In this way, the real X_{re} and imaginary X_{im} part of the signal $x(t)$ are given by:

$$X_{re} = \frac{2}{N}\sum_{k=0}^{N-1} x_k \cos\left(\frac{2\pi}{N}k\right), \quad (8)$$

$$X_{im} = \frac{2}{N}\sum_{k=0}^{N-1} x_k \sin\left(\frac{2\pi}{N}k\right), \quad (9)$$

where k is the index of sample.

3.2.3 Step 3

In this step, two methodologies for fundamental frequency estimation described in section II: method based on discrete Fourier transform, and Prony-Fourier-based algorithm were applied.

To better see, all these steps proposed methodology is showed in Fig. 3.

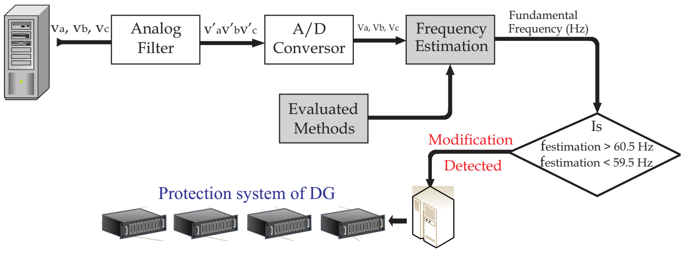

Fig. 3. Methodology of frequency estimation architecture.

4 Response of the Algorithms to Experimental Waveform Records

4.1 Electric Power Distribution System Test

The power system used in this paper is shown in Fig. 4 and based in [31]. It is a 132 kV transmission line Thevenin equivalent connected to a transformer 132/33 kV in delta/wye-ground.

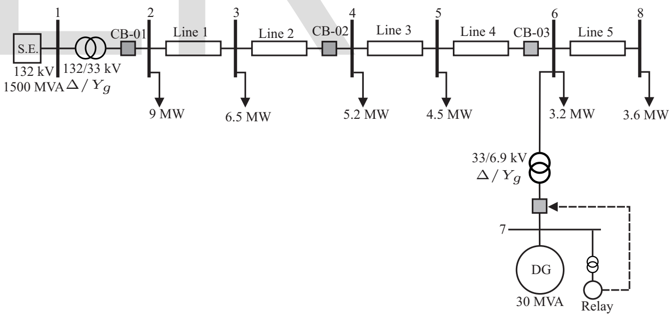

Fig. 4. Electric power distribution system with DG.

The 33 kV distribution system is composed of 5 equivalent RL branches, Table 1. This distribution system is connected to a synchronous generator of 30 MVA.

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

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 model [31]. Synchronous generators were represented by a sixth-order three-phase model in the rotor

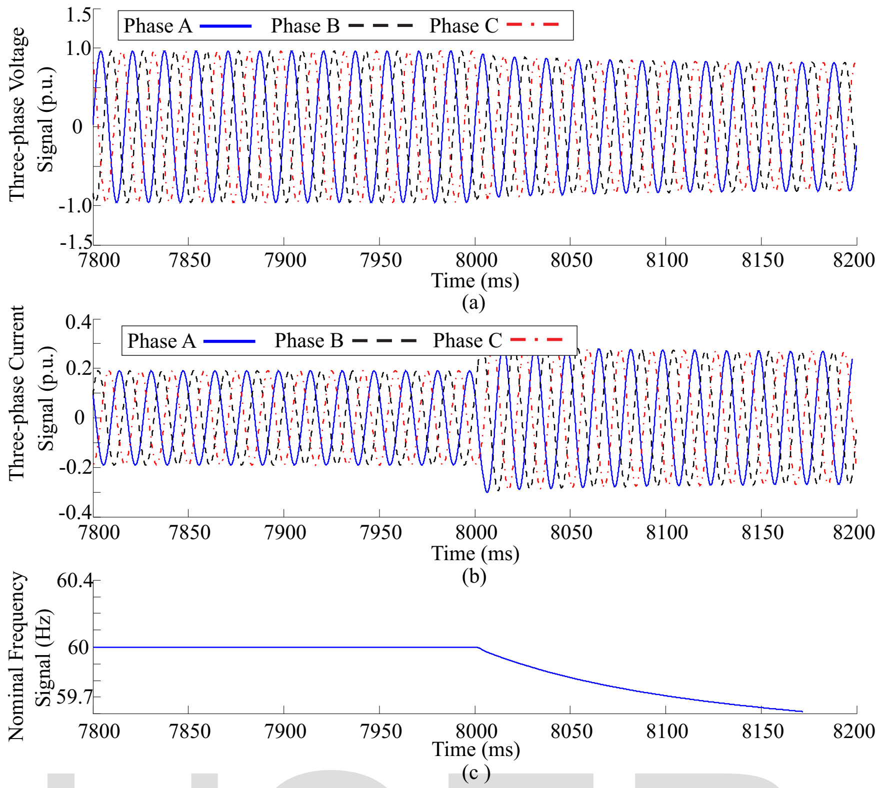

Fig. 5. Output signal of electric power system. (a) Three-phase voltage signal (in per unit). (b) Three-phase current signal (in per unit). (c) Nominal frequency (Hertz).

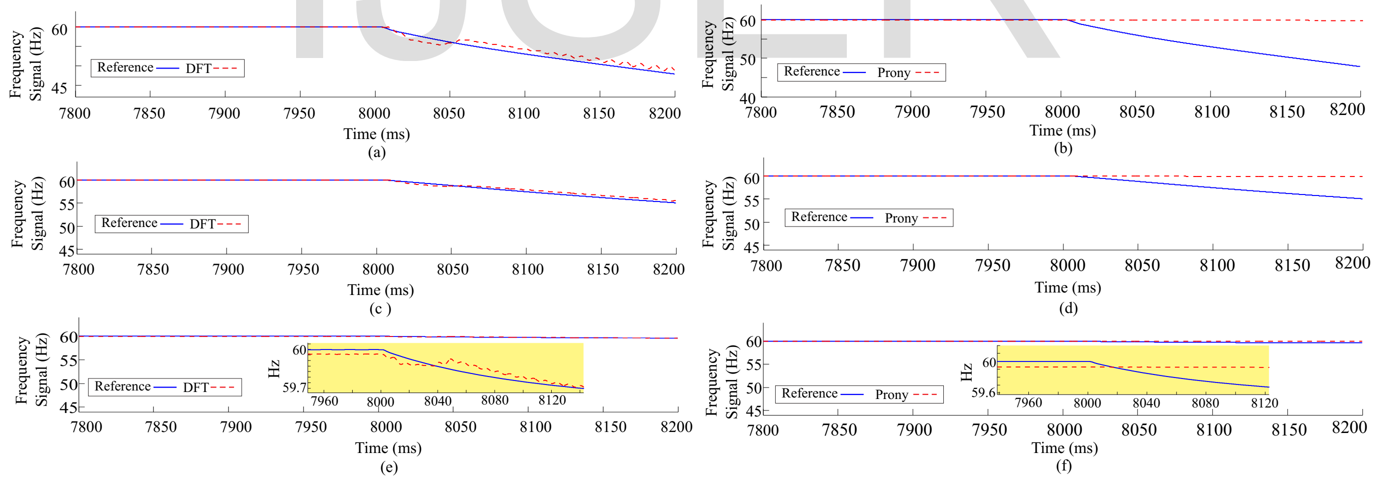

Fig. 6. Signals out of frequency estimators using DFT and Prony method. Frequency estimated in (Hz): (a) and (b) with 100% of the nominal power of DG, (c) and (d) with 50% of the nominal power of DG and (e) and (f) with 10% of the nominal power of DG.

reference frame. The generators were equipped with an automatic voltage regulator represented by the IEEE type 1 model [32].

The simulation results presented were all processed using Matlab®. The sampling frequency was set to 20 kHz or 333 samples per cycle 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.

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 $t = 8$ s, which remains open until the end of the simulation at $t = 10$ s. The frequency estimation is measuring the parameters in the bus of DG. The power imbalance of the islanded system is gradually varied from 0.1 to 1 p.u., referred to the MVA rating of the generator.

The signals of the three-phase power system that is used as signals input to evaluated of the frequency estimation methods (Fig. 5). However, in this paper, for frequency

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estimation, only one phase was used for the estimation methods.

In Fig. 6 is depicted the signal output of the DFT and Prony method to 10%, 50%, 100% of the nominal power (Pn) of the DG. In this figure can be observed the variation of the frequency due to the power imbalance of DG.

4.2 Test Results

To evaluate the performance of the frequency estimators, the frequency relative errors were computed for each Matlab ® simulation as

$$\varepsilon_{\tau}(\%) = \frac{f - f_{est}}{f}.100, \qquad (10)$$

where f is the reference frequency of the system, f_{est} is the estimated frequency using DFT and Prony method.

To know the behavior, performance and robustness of the evaluated methods were simulated different cases on the electric distribution system. Here, was simulated the distribution system with DG varying the nominal power of the synchronous machine (i.e., DG) installed on the distribution system, variations were of $10\%Pn$, $30\%Pn$, $50\%Pn$, $70\%Pn$, $100\%Pn$.

The estimation error of DFT method is depicted in Fig. 7 referent to the steady state and Fig. 8 referent to the transient state (i.e.: in the islanding condition of the DG).

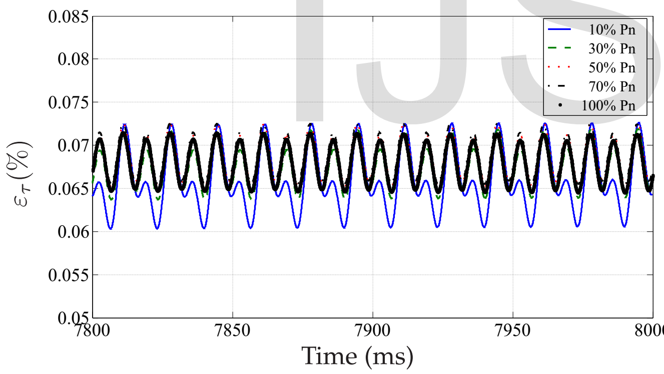

Fig. 7. Estimation error $\varepsilon_{\tau}(\%)$ of DFT method depicted to 10%, 30%, 50%, 70%, 100% of the nominal power (Pn) of the DG and in steady state of the distribution system.

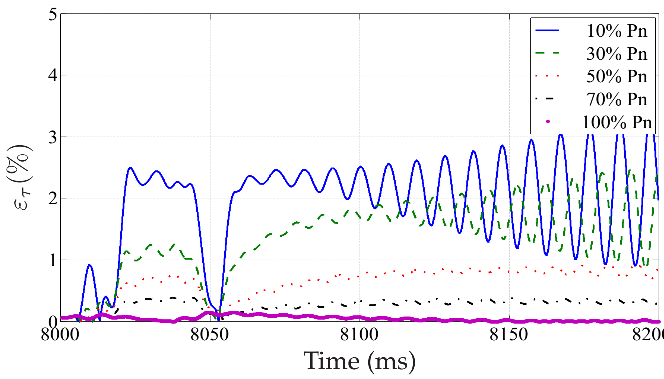

Fig. 8. Estimation error $\varepsilon_{\tau}(\%)$ of DFT method depicted to 10%, 30%, 50%, 70%, 100% of the nominal power (Pn) of the DG and in transient state of the distribution system, during the islanding condition.

The estimation error of Prony method is depicted in Fig. 9 referent to the steady state and Fig. 10 referent to the transient state (i.e.: in the islanding condition of the DG).

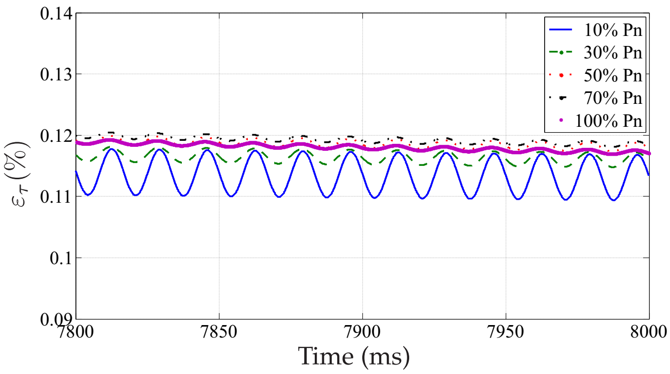

Fig. 9. Estimation error $\varepsilon_{\tau}(\%)$ of Prony method depicted to 10%, 30%, 50%, 70%, 100% of the nominal power (Pn) of the DG and in steady state of the distribution system.

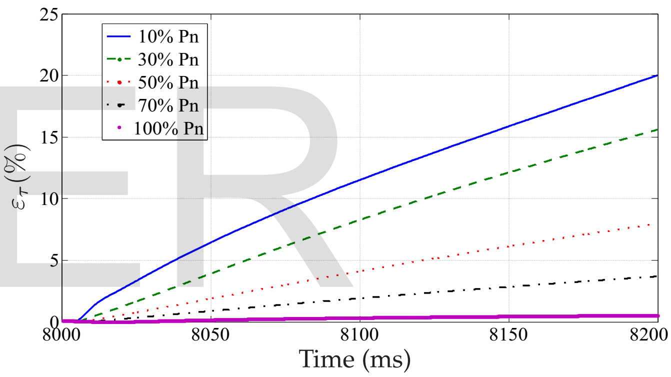

Fig. 10. Estimation error $\varepsilon_{\tau}(\%)$ of Prony method depicted to 10%, 30%, 50%, 70%, 100% of the nominal power (Pn) of the DG and in transient state of the distribution system, during the islanding condition.

The DFT method provides good results, even for the signals contaminated with significant noise or harmonics due to the islanding condition of DG. The DFT provides satisfactory performance and could be used in digital power system protection relays or in a digital protection of islanding detection of distributed generation systems.

5 Conclusion

This paper describes the evaluation of two frequency estimation methods, such as discrete Fourier transform (DFT) and Prony-Fourier-based applied for the accurate and fast determination of the main fundamental frequency in a power system with distributed generation (DG) in islanding condition. After antialiasing 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 on the processed signals. The evaluated methods provide accurate and fast when estimating the fundamental frequency of the distributed generation signals in islanding condition. The DFT and Prony method they presented the best result on the frequency estimation during the stead estate. However, the DFT method presented the best result during the transient state or in islanding condition of the DG, in comparison with the Prony method. The performance of Prony was reduced in comparison with the DFT method in all simulation cases. Results obtained from various simulation cases, i.e. with the variation of the nominal power DG, demonstrate the effectiveness of the DFT technique in comparison with the other evaluated method.

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