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On-line Power Frequency Estimation Using Real-Time Wavelet Transform

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Abstract:

This paper proposes a new technique for estimating the fundamental frequency of power system in harmonic condition by using real-time wavelet transform. Indeed, the fundamental component of the distorted system voltage is extracted using real-time wavelet transform and then the frequency of the fundamental component can be estimated using a simple mathematical method. In spite of other methods for estimating the power frequency, which are so complicated and time consuming to have a good accuracy or simple methods which are not accurate in presence of harmonic, the proposed method can extract the power frequency not only so fast but also with acceptable accuracy. The fast operation of this technique makes its response more accurate in dynamic and transient conditions. Simulation results validate the proposed technique for power frequency estimation in harmonic condition. Also, comparisons of this technique and least square method are presented to show the advantageous of this novel method.

Key Words: power quality, power frequency estimation, real-time wavelet transform, Multi-Resolution Analysis (MRA)

1. Introduction

Industries with sensitive electrical loads are becoming more dependent on the power quality of power supply system [1]. Power system frequency, as a key index of power quality, can be indicative to unexpected system faults and disturbances. For a large, stiff power system, variation in frequency will usually slow due to large mechanical inertia of the system [2]. In this case, estimation of the main power frequency is an important for the control and protection of power system. However, for a smaller system, frequency changing will be correspondingly faster and the algorithm with fair dynamic property is required.

In either case, for compensating distortion of voltage and current of power system using active power filter, most of the well-known control strategies depend on power frequency of the system. For instance, if there is a slight frequency drifting FFT can not extract the exact value of magnitude of the base frequency (power line frequency) [3].

A variety of techniques and algorithms have been developed and evaluated for real-time estimation of power system frequency in recent years. The simplest method is zero-crossing detection technique and its modification by using curve fitting of voltage samples [4]. Although, this algorithm is relatively simple and reliable under low level noise contamination, the accuracy will be deteriorated in the presence of heavy harmonic distortion, power system transient and dynamic condition.

Least square error technique [5] Discrete Fourier Transform (DFT) [6] technique often used assumes sinusoidal waveforms of one frequency and is unreliable in the presence of distortion. Other techniques utilizing recursive least square estimation [7] and recursive Newton techniques [8] are complicated and time consuming for extracting the power frequency in presence of harmonic and they are not suitable for real-time applications.

Some adaptive methods, which are based on feedback loop are adapted to improve the performance of approaches based on Fourier algorithm, by either timing the sampling interval [9] or adjusting observation window length [10] or changing the nominal frequency in Fourier algorithm iteratively [11] and amending the gain of orthogonal filters in Fourier algorithm recursively [12-13] according to the latest frequency estimation.

Several kind of nonlinear curve fitting techniques have been proposed to estimate not only fundamental frequency but also harmonic. The adapted techniques, such as extended Kalman filtering [14-15] and adaptive notch filter [16] can not provide a precise measurement over a wide frequency range. A revised digital algorithm named Smart Discrete Fourier Transform (SDFT) [17] can provide the exact solution of power frequency recursively, but it have trade off between accuracy, the length of observation window and computation complexity. These methods require considerable computational resources and, therefore, can not be economically implemented.

A new numeric technique and its practical implementation are presented in [18]. By defining the frequency estimation as an unconstrained optimization problem, a variety of optimization techniques such as genetic algorithm [19] and artificial neural network [20-22] are adopted to achieve high measurement accuracy over a wide range of frequency deviation and fast algorithm convergence.

In this paper, a new technique for fast estimating the power frequency is proposed. In the proposed technique, the harmonic components of the waveform are eliminated using wavelet transform and Multi-Resolution Analysis (MRA) and then the frequency of the fundamental component can be extracted using a simple and fast technique for real-time frequency estimation application. In section 2 and 3, principle concept of the proposed method will be discussed. Comparison the proposed technique and least square method through simulation results are presented in section 4 for validating the proposed technique. Section 5 concludes this paper.

2. Wavelet Transform and MRA

The wavelet transform is a mathematical tool, much like a Fourier transform in analyzing a stationary signal that decomposes a signal into different scales with different levels of resolution by dilating a signal prototype function. Unlike the Fourier transform which gives a global representation of a signal, the wavelet transform provides a local representation (in both time and frequency) of given signal; therefore, it is suitable for analyzing a signal where time-frequency resolution is needed.

A wavelet transform maps the time-domain signals in real-valued time-frequency domain, where the signals are described by the wavelet coefficients [23]:

$$f(t) = \sum_{k=0}^{2^{j_0-1}} c_{j_0,k}\phi_{j_0,k}(t) + \sum_{j\geq j_0}^{N-1}\sum_{k=0}^{2^{j-1}} d_{j,k}\psi_{j,k}(t) \qquad (2)$$

with:

$$c_{j_0,k} = \langle f(t), \phi_{j_0,k}(t)\rangle \text{ and } d_{j,k} = \langle f(t), \psi_{j,k}(t)\rangle \qquad (3)$$

where j and k are wavelet frequency scales, wavelet time scale, respectively, and c and d are wavelet coefficients.

Time-varying signal can be represented in terms of its frequency components, using MRA. For instance, if the source signal contains 1000 samples of a time domain waveform, the signal is divided into two domains with 0-250 Hz and 250-500 Hz frequency components by using one-stage MRA.

For estimating the frequency of fundamental component of system voltages, the sampling frequency should be defined accurately by making trade off between the computation time and the accuracy of the response. For obtaining the fundamental component waveform, n-stage MRA should be implemented to the sampled waveform. For instance, in previous example, n should be took equal 8 to eliminate the effect of harmonic components. It is assumed that third harmonic of the voltages is eliminated by the transformer of the system. Fig. 1 shows an 8-stage MRA for the waveform of previous example.

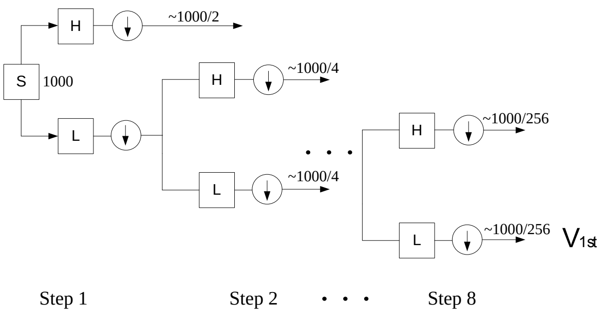

Fig. 1. 8-stage signal decomposition using MRA

For real time applications, the real time wavelet transform should be used to determine the fundamental component of system waveforms. For this purpose, a synthetic wave form which is the combination of the original waveform and its symmetric is used as source signal (Fig. 2).

If the amplitude of the waveform varies against time, the response of the algorithm may be became disrupted, however, curve fitting method will be used for predicting the alteration of the waveform.

Fig. 2 shows a typical distorted waveform that its amplitude increases at the first of third cycle which is shown in the figure and best fit (or curve fitting) method predicts the amplitude of fundamental component amplitude of the waveform and produces

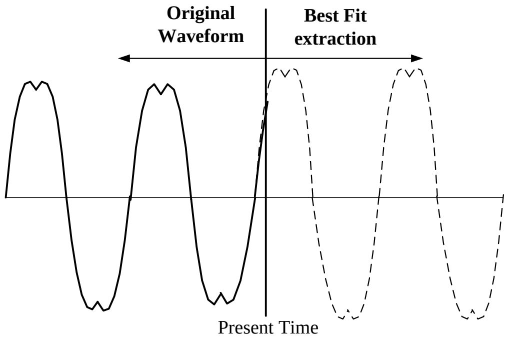

Fig. 2. Synthetic waveform used for real-time wavelet transform

dashed line waveform with respect to the proportion of the estimated fundamental component amplitude and the fundamental component amplitude of previous cycle.

3. Frequency Estimation Method

Let $v_1(t)$ be the fundamental component of the distorted voltage of the system obtained using MRA, so, it can be explained as:

$$v_1(t) = V_1 \sin(\omega_1 t + \phi_1) \quad (3)$$

where V_1, ω_1 and ϕ_1 are fundamental amplitude, frequency and phase angle, respectively. Considering equation (3) for three successive sampled point of $v_1(t)$, the below statements will be obtained:

$$v_1(t)\big|_{t=0} = V_1 \sin\phi_1 \quad (4)$$

$$v_1(t)\big|_{t=-\Delta t} = -V_1 \sin\omega_1\Delta t \cos\phi + V_1 \cos\omega_1\Delta t \sin\phi_1 \quad (5)$$

$$v_1(t)\big|_{t=\Delta t} = V_1 \sin\omega_1\Delta t \cos\phi_1 + V_1 \cos\omega_1\Delta t \sin\phi_1 \quad (6)$$

where Δt is the sampling time interval. Summing equations (5) and (6) will result as:

$$v_1(t)\big|_{t=\Delta t} + v_1(t)\big|_{t=-\Delta t} = 2V_1 \cos\omega_1\Delta t \sin\phi_1 \qquad (7)$$

And then from equations (7) and (4); we can write:

$$\cos\omega_1\Delta t = \frac{v_1(t)\big|_{t=\Delta t} + v_1(t)\big|_{t=-\Delta t}}{2v_1(t)\big|_{t=0}} \qquad (8)$$

So, the fundamental power frequency can be obtained from equation (8) as:

$$f_1 = \frac{f_s}{2\pi}\cos^{-1}\left(\frac{v_1(t)\big|_{t=\Delta t} + v_1(t)\big|_{t=-\Delta t}}{2v_1(t)\big|_{t=0}}\right) \qquad (9)$$

where f_s is sampling frequency. It is noted that the power frequency is estimated with one sampling time interval delay, because in practice, the sample points are obtained from $t = 0, -\Delta t, -2\Delta t$ instead of $t = -\Delta t, 0, +\Delta t$.

Fig. 3 shows a sinusoidal waveform that its fundamental frequency varies with time according to Fig. 4. Fig. 4 shows the frequency of the fundamental component that jumps at 0.06 and 0.08 seconds, also, the estimated frequency using the proposed method is shown in Fig. 4. It is shown that if the frequency of the power system jumps to a higher or lower value, the estimated power frequency using the proposed method can be obtained so fast. In practice, the oscillation of the frequency is so slow because the mechanical system situation varies slower than electrical system. Fig. 5 shows the frequency of a waveform (dashed line) which varies slowly. The estimated frequency obtained using proposed algorithm is shown in Fig. 5 by black line. In this case, the accuracy of the response decreases. It is due to the slope of the frequency variation, which causes different frequency for each successive sampling point (equations (5) and (6)). In this condition, the power frequency is determined with error, but, if the fundamental frequency jumps to another value (previous example), after passing three sampled points, the frequency of each sample will be became equal and so the estimated frequency obtained more accurately and so fast.

For solving the problem for the case of slow variations, the frequency of each sample should be considered different. For this purpose, equations (5) and (6) are defined as:

$$v_1(t)\big|_{t=-\Delta t} = -V_1 \sin(\omega_1 + \Delta\omega_{-1})\Delta t \cos\phi_1 + V_1 \cos(\omega_1 + \Delta\omega_{-1})\Delta t \sin\phi_1 \qquad (10)$$

$$v_1(t)\big|_{t=+\Delta t} = V_1 \sin(\omega_1 + \Delta\omega_{+1})\Delta t \cos\phi_1 + V_1 \cos(\omega_1 + \Delta\omega_{+1})\Delta t \sin\phi_1 \qquad (11)$$

where

$$\Delta\omega_{-1} = \omega(t)\big|_{t=-\Delta t} - \omega(t)\big|_{t=0} \qquad (12)$$

$$\omega_1 = \omega(t)\big|_{t=0} \qquad (13)$$

$$\Delta\omega_{+1} = \omega(t)\big|_{t=+\Delta t} - \omega(t)\big|_{t=0} \qquad (14)$$

Same as before, by summing equations (10) and (11) and solving the result for $\Delta\omega_{+1}$, frequency of power system can be obtained as:

$$f(t)\big|_{t=+\Delta t} = \frac{f_s}{2\pi}\cos^{-1}\left[\frac{(v_1(t)\big|_{t=+\Delta t} + v_1(t)\big|_{t=-\Delta t})}{v_1(t)\big|_{t=0}} - \cos(\omega_1 + \Delta\omega_{-1})\Delta t\right] \quad (15)$$

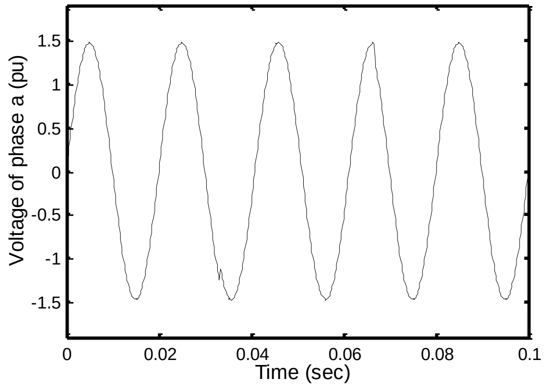

Fig. 3. Voltage of phase (a) with step frequency

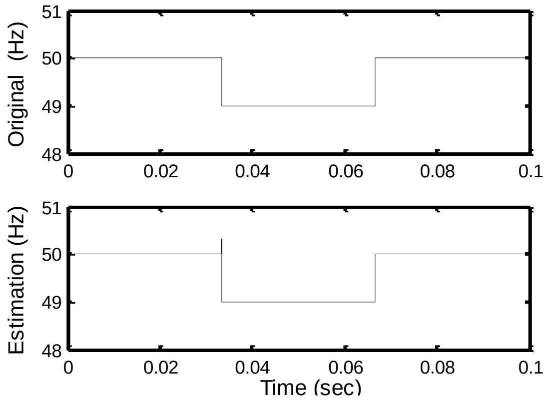

Fig. 4. Waveform frequency and estimated frequency using proposed algorithm

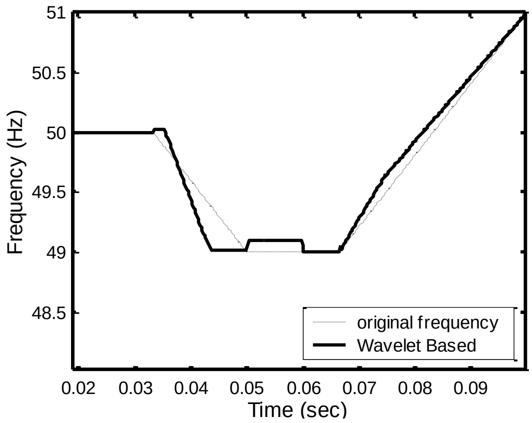

Fig. 5. Power frequency estimation using proposed technique

In this case, it is assumed that the value of $\Delta\omega_{+1} \cdot \Delta t$ and $\Delta\omega_{-1} \cdot \Delta t$ and so $\Delta\omega_{+1} \cdot \Delta t + \Delta\omega_{-1} \cdot \Delta t$ are very small and the statements which contain these values are ignored. The accuracy of the proposed method increases using the second solution for estimating the frequency. In spite of the first solution, recent solution estimates the frequency of the system without any time delay.

Fig. 6 shows the fundamental frequency of a typical waveform (same as Fig. 5) and the estimated frequency using recent method. It is shown that the accuracy of estimation especially for continuous variations is improved using second solution.

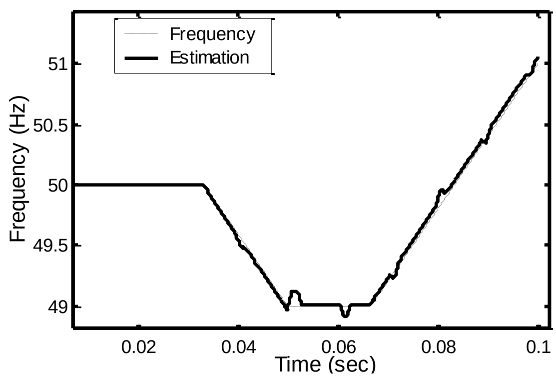

Fig. 6. Power frequency estimation using second solution of proposed technique

4. Simulation Results

The proposed control strategies will be validated through simulation results using MATLAB/SIMULNIK software package. In this section, second solution of the proposed method is used to estimate the fundamental power frequency. Sampling frequency is selected 5 kHz. Therefore, by taking 100 samples in one cycle of the system voltages, trade off is taken between the accuracy of the response and computing time.

The nominal phase voltage and frequency of the system used in this simulation are $20kv/\sqrt{3}$ and $50Hz$, respectively. The system contains nonlinear loads which make the source voltages distorted as shown in Fig. 7 for phase (a). Least square method [5], [24] is relatively simple method, so, in this simulation this method is used to estimate the power frequency of the system.

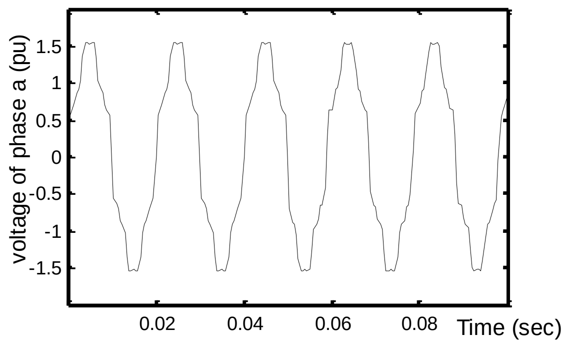

Fig. 7. Voltage of phase (a) with harmonic distortion

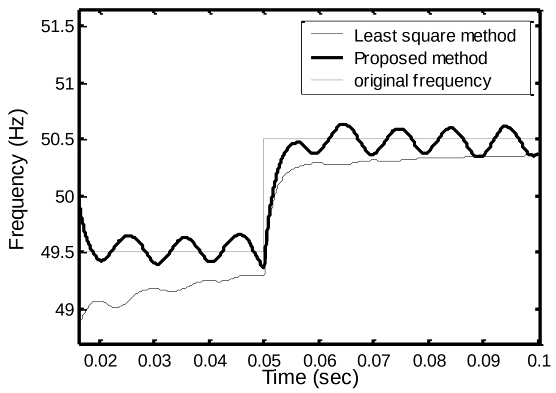

Fig. 8. Power frequency estimation

For estimating the fundamental power frequency in presence of harmonic, the least square method should be developed for limited number of harmonic components. It can estimate the exact value of power frequency in presence of low level harmonic components. Fig. 8 shows the fundamental frequency of the system and the estimated frequency obtained using both least square method and proposed technique. It can be found that the accuracy of the proposed technique result, especially for large frequency oscillation is more acceptable then least square method. The great error in the result of least square method is due to high harmonic pollution of system voltages.

One of the best advantageous of the proposed technique is its fast frequency extraction which makes this technique suitable for small power networks with great frequency oscillation. Moreover, if the fundamental component of source voltages varies with time or the harmonic components of the voltages change, most of the well-known algorithm can not estimate the exact value of power frequency immediately after variations. Fig. 9 shows the source voltage of the power system that the amplitude of the fundamental component increases 10 percent at 0.06 sec by disconnecting one of the great loads of the system. In this case, harmonic pollution of the voltages assumed to be low level aim to show the performance of the methods in dynamic condition. The estimations of its fundamental frequency obtained by least square and proposed method are shown in Fig. 10. It is shown that the performance of the proposed technique is better in dynamic conditions. The error in the proposed technique result mostly is caused by the error of extracting the fundamental component of the voltage waveform by using wavelet decomposition and MRA technique.

The great variation of the least square method is affected by the number of samples used in the algorithm. the lower the number of samples, the lower response accuracy in steady state condition, but the higher number of samples causes better accuracy in steady state condition and lower speed and so accuracy in dynamic condition. The relatively accurate response of the proposed technique in presence of harmonic is due to the fewer sampled point used in this technique in the condition that the harmonic components eliminated using MRA. Therefore, the proposed technique can extract the power frequency not only so fast but also with acceptable accuracy.

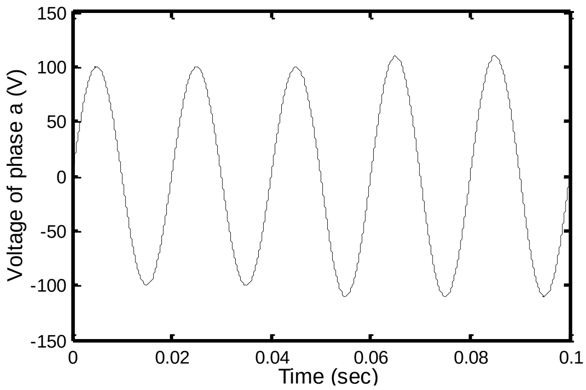

Fig. 9. Voltage of phase (a) that its amplitude increase in 0.06 sec

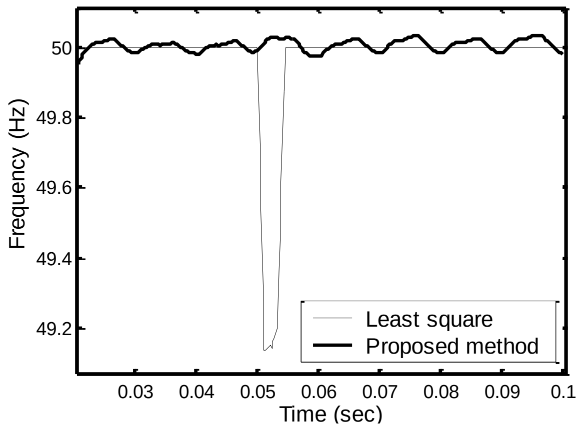

Fig. 10. Power frequency estimation

5. Conclusion

In this paper, a new algorithm for estimating the fundamental frequency of power system is proposed. Most algorithms and techniques, proposed for extracting the frequency of the system, are not suitable for real-time applications. The accurate techniques, such as Newton algorithm, optimization methods and iterative techniques are time consuming and they are not suitable for real-time estimating the frequency in harmonic condition. Proposed technique is based on wavelet decomposition and Multi-Resolution Analysis to extract the fundamental component of the distorted waveform and a simple straight method to estimate the frequency of the sine waveform.

The proposed technique provides a simple implementation with acceptable accuracy especially in dynamic and harmonic condition, so this method seems to be suitable for real-time applications which the speed of estimation plays an important role.

Comparison the proposed technique and modified least square method (which is relatively simple and fast) as well as simulation results in various conditions validate the proposed method. Simulation results show that the proposed technique can extract the power frequency not only so fast but also with acceptable accuracy.

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