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ANALYSIS OF A SIMPLE EFFECTIVE FREQUENCY ESTIMATOR BASED ON LEAST SQUARES NEW APPROACH

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Abstract- Due to deregulation, competitive electricity market, expansion of transmission and distribution network, increased applications of power electronics make the power system more complex. As a result of these changes, the determination of accurate power system frequency becomes more difficult. In this work, recently proposed Least squares new approach based frequency estimation algorithm has been implemented. The paper includes the hardware architecture and the software program. To demonstrate the performance of the algorithm for on line frequency estimation, algorithm was tested in laboratory with a data acquisition card using Matlab as a software tool. The effects of the critical parameters such as data window size, and sampling frequency on the performance of the algorithm are also discussed in this paper.

Keywords: Frequency Estimation, Least Squares Method, Matlab, Sampling Rate, Window Size.

I. INTRODUCTION

In a power system, frequency is the most important and fundamental parameter for power system analysis, operation and control. The Frequency can represent the dynamic balance between load and generating power hence, fast and precise estimation of frequency is vitally necessary. In last two decades, power industries have been deregulated, restructured and decentralized, and increased applications of power electronic makes the power system more complex. As a result estimation of accurate power system frequency more difficult. The quality of a power generating system is important in many applications [1]. A change in frequency has negative effects in some of the applications [2].

In the past, several frequency estimation algorithms / techniques have been introduced. The least error squares technique (LES) [3-4], the recursive least error squares technique and the least absolute value technique were used for frequency estimation [5-8]. The zero crossing detection technique and its modifications most commonly used to estimate the frequency of the signal [9].

Leakage effect of the fast Fourier transform (FFT) is another method to estimate frequency [10].Another conceptually similar method is based on the phasor angle analysis [11-12].The concept of Kalman filtering (KF) is also used for power system frequency estimation [13-15], wavelet approach is another method used for power frequency estimation [16].

The adaptive neural network (ANN) is the basis for another set of approaches for power system frequency estimation in power system [17-18]. The concept of three phase locked loop (PLL) and quadrature PLL (QPLL) is also widely used for phase and frequency estimation [19-20], adaptive filtering [21-22] and so on. However, most of the aforementioned methods have tradeoff between accuracy and speed.

In this paper, analysis of frequency estimation based on Least squares new approach is presented. The work presented in this paper is implemented in laboratory with data acquisition card using Matlab as a software tool for on line frequency estimation. The experimental results show that the frequency estimation method based on Least squares new approach could be the optimal frequency measurement method, and thus can be used for frequency measurement devices. The rest of the paper is organized as follows: Section II is a brief description of the frequency estimation method. Section III describes hardware structure and software tool used for algorithm testing. Section IV presents the results obtained. In section V, the effects of the critical parameters on the performance of the algorithm is discussed. Finally, section VI summarizes the conclusion reached in this study.

II. BRIEF OVERVIEW OF FREQUENCY ESTIMATION METHOD

The objective of this section is to provide a very general perspective of the frequency estimation algorithm used for real time power system frequency estimation [14]. Consider a sinusoidal power system voltage signal of frequency $\omega = 2\pi f$ as follows:

$$v(t) = V_m \cos(\omega t + \phi_0) \quad (1)$$

where, V_m is the voltage amplitude, ϕ_0 is the initial phase angle. Suppose that v(t) is sampled with a sampling frequency f_s [Hz] to produce sample {$v(k)$}

$$v(k) = V_m \cos(\omega t + \phi_0) \quad (2)$$

Similarly, v_{k-1} and v_{k+1} are represented as follows:

$$v(k-1) = V_m \cos(\omega t_{k-1} + \phi_0) \quad (3)$$

$$v(k-1) = V_m \cos(\omega t_{k-1} + \phi_0) \quad (4)$$

Since $t_{k\pm1} = t_k \pm \Delta t$, using trigonometric identities Equation (3) and Equation (4) can be expanded as follows:

$$v(k-1) = V_m \cos(\omega t_{k-1} + \phi_0)\cos(\omega \Delta t) + \\ +V_m \sin(\omega t_{k-1} + \phi_0)\sin(\omega \Delta t) \quad (5)$$

$$v(k+1) = V_m \cos(\omega t_{k-1} + \phi_0)\cos(\omega \Delta t) - \\ -V_m \sin(\omega t_{k-1} + \phi_0)\sin(\omega \Delta t) \quad (6)$$

Combining Equation (5) and Equation (6), results in:

$$v(k-1) + v(k+1) = 2v_k \cos(\omega \Delta t) \quad (7)$$

$$f_k = f_s / 2\pi \cos^{-1}\left(v(k-1) + v(k+1)\right) / 2v_k \quad (8)$$

Now, cos($\omega\Delta t$) can be estimated using the least squares method. One must calculate pseudo inverse of $v(k)$ [2]. Let G denoted the pseudo inverse of $v(k)$. Therefore:

$$G = \left(V_k^T V_k\right)^{-1} V_k^T \quad (9)$$

$$G = V_k^T \Big/ \left(V_k^T\right) \quad (10)$$

$$\cos(\omega \Delta t) = V_k^T \left(V_k^- + V_k^+\right) \Big/ \left(2V_k^T V_k\right) \quad (11)$$

Finally, the frequency is estimated using the following formula:

$$f_k = f_s / (2\pi) \cos^{-1} \frac{V_k^T \left(V_k^- + V_k^+\right)}{2V_k^T V_k} \quad (12)$$

III. EXCREMENTAL SETUP AND DATA COLLECTION

The least squares new approach based frequency estimation algorithm was implemented in laboratory on designed and developed prototype hardware to practically verify the on line results. Figures 1 and 2 show the setup used for experimentation. The hardware structure consist of analog scaling, isolation and MS window based host computer. The isolation and analog scaling block consist of the gain circuit and voltage transducer.

The function of this block is to reduce the levels of voltage signals to equivalent voltage signals and to prevent the clamping of the input voltage signal. Also isolate the microcomputer block and power supply. The microcomputer block consists of Advantech data acquisition card and MS XP based host computer. The data acquisition card can sample and digitalize input signals .The data acquisition and proposed frequency estimation algorithm was written in Matlab. The input signals are recorded at a sample rate of 850, 1000, 1200, 2500, and 5000 samples/sec.

The hardware key specifications are as follows: V_{ac} = 230 V, the voltage transducer ratio is 230/6 V. The gain control of gain 0.5, R_f=5kΩ and R_i=10kΩ. The input voltage at the operational amplifier is 9V and voltage available at output is 4.5V. The specifications of a data acquisition card is PCLD-8710-100KS/S, 12 bit, 16 channel PCI multifunction card-Advantech Co. Ltd.

Figure 1. Gain control circuit

Figure 2. Experimental set up for on line frequency estimation

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

In this section, we investigate the performance of Least squares new approach algorithm for online frequency estimation with and without filtering is investigated. The effect of data window size, sampling rate on the algorithm performance is also discussed. In order to demonstrate the effectiveness of the proposed algorithm practically, use to test voltage signal from the single phase 230 V mains which includes the nominal frequency. The potential transformer is used to reduce the voltage level. Further the gain control circuit is used to reduce the voltage by the ratio of 1:2.

The output of the gain control circuit is given to Advantech card. These signals are recorded at various sampling rates such as 850, 1000, 1200, 2500, 5000 samples/sec. The frequency estimation algorithm discussed in section II was used for real time frequency estimation. In simulation cases the sampling frequencies are 850, 1000, 1200, 2500, 5000 samples/sec with data window length = 9, and the nominal frequency is assumed to be 50 Hz.

Table 1 shows the combinations of parameters used in online analysis of Least square new approach algorithm for estimating the frequency. The behavior of the algorithm with and without filtering is examined. Some of the results are presented in this section.

Table1. Combination of parameters used for algorithm testing

Window length	Sampling rate (Hz)	Time (sec)
9	850	0.4 cycle
	1000	
	1200	
	2500	
	5000	

A. Case I - Real Time Frequency Estimation - without Filtering

Figures 3, 4, 5, 6, and 7 present the frequency response of the algorithm which uses a data window of 9 samples at sampling rates 850,1000, 1200, 2500, and 5000 Hz, respectively. Table 2 illustrates the relative frequency estimates with the proposed method for case I. Comparing to the results obtained for data window size of 9 at sampling rates 850, 1000, 1200, 2500, 5000, samples/sec the estimated frequency is in the range of 44.06 Hz to 49.25 Hz.

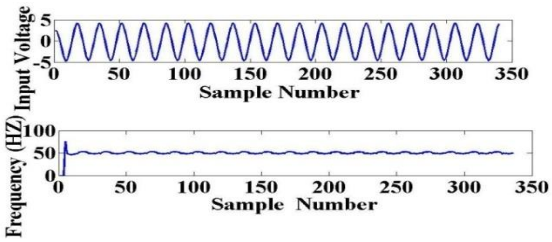

Figure 3. Estimated Frequency, duration = 0.4 cycle, sampling frequency 850 Hz

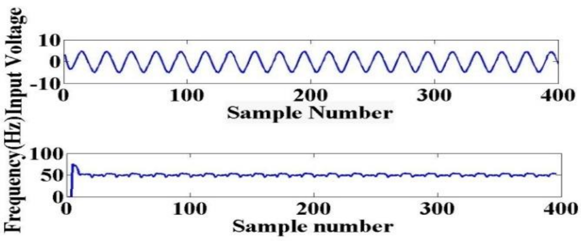

Figure 4. Estimated Frequency, duration = 0.4 cycle, sampling frequency 1000 Hz

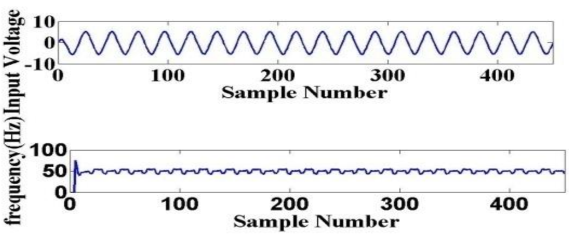

Figure 5. Estimated Frequency, duration = 0.4 cycle, sampling frequency 1200 Hz

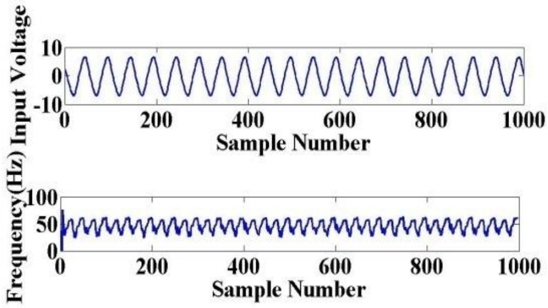

Figure 6. Estimated Frequency, duration = 0.4 cycle, sampling frequency 2500 Hz

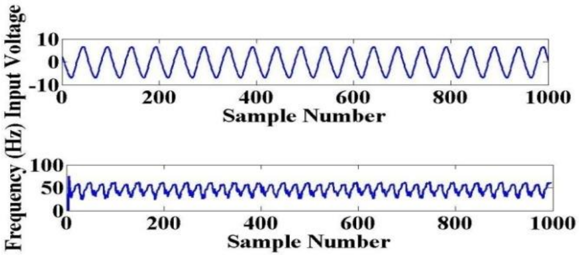

Figure 7. Estimated Frequency, duration = 0.4 cycle, sampling frequency 5000 Hz

Table 2. Real time estimated frequency - without filtering

Sampling frequency (Hz)	Estimated frequency (Hz)		
	Min.	Max.	Avg.
850	5.93	5.06	8.95
1000	129.71	58.91	9.25
1200	-129.71	58.95	8.11
2500	-129.71	4.72	4.06
5000	-129.71	52.80	4.47

B. Case II - Real Time Frequency Estimation - with Filtering

Figures 8, 9, 10, 11, and 12 present the frequency response of the algorithm which uses a data window of 9 samples at sampling rates 850,1000, 1200, 2500, and 5000 Hz respectively. Table 3 illustrates the relative frequency estimates with the proposed method for case II. Comparing to the results obtained for data window size of 9 at sampling rates 850, 1000, 1200, 2500, 5000, samples/sec the estimated frequency is in the range of 49.62 Hz to 49.68 Hz which is quite better than results obtained for frequency estimation without filtering. Thus, least squares new approach based real time estimation of frequency with filtering, gives better results.

Least error square, the recursive least error and the least absolute value frequency estimation techniques were implemented off line to measure the off nominal, near nominal, and nominal frequency. They produce good estimation of power system frequency. Such algorithm needs much more time and computation for frequency estimation if they are applied in some real-time measurement cases. Least error squares new approach provides fast and good frequency estimation over a wide range interested frequency, and the computation requirement is modest for on line implementation. However, the drawback of this algorithm is inefficient when smallest data window (three samples) is used.

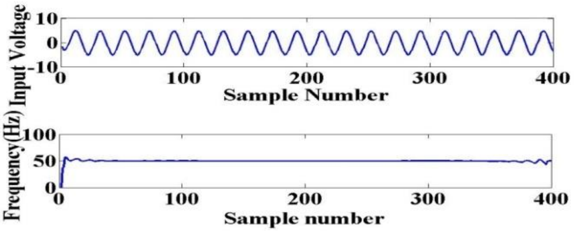

Figure 8. Estimated Frequency, duration = 0.4 cycle, sampling frequency 850 Hz

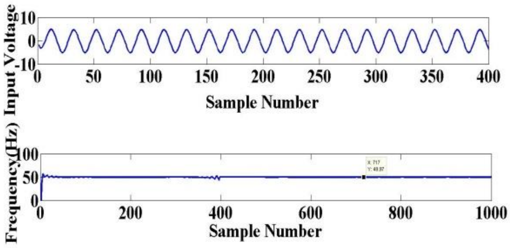

Figure 9. Estimated Frequency, duration = 0.4 cycle, sampling frequency 1000 Hz

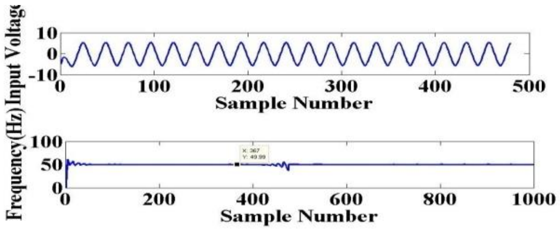

Figure 10. Estimated Frequency, duration = 0.4 cycle, sampling frequency 1200 Hz

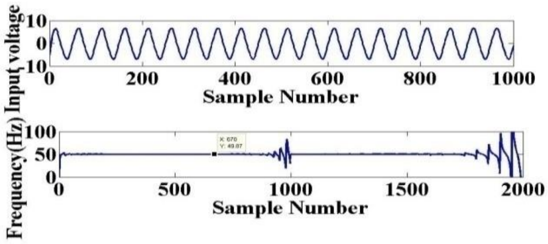

Figure 11. Estimated Frequency, duration = 0.4 cycle, sampling frequency 2500 Hz

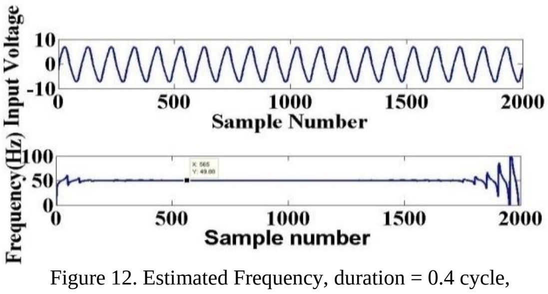

Figure 12. Estimated Frequency, duration = 0.4 cycle, sampling frequency 5000 Hz

Table 3. Real time estimated frequency - with filtering

Sampling frequency (Hz)	Estimated frequency (Hz)		
	Min.	Max.	Avg.
50	7.28	1.25	8.95
000	7.28	57.13	9.25
200	37.28	61.29	8.11
500	19.77	3.04	4.06
000	-46.79	31.88	4.47

V. FACTORS AFFECTING THE ALGORITHM

An algorithm which estimates the real time frequency from sampled input signals has been discussed in previous section. This algorithm is affected by many factors, such as the size of data window, sampling rate,. In this section, implications of using different sizes of data windows, and different sampling rates are investigated.

A. Data Window Size

Generally speaking there are two types of data windows [23]. A moving window continuously updated and including newer samples and discarding older samples. On the other hand, all growing window means that the new data points are added without deleting the older data point. For discussing the effect of data window size, here mean of square error (MSE) of exact and estimated frequency at time t_k, an index of accuracy [24], is calculated for different data window length such as 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, 27 and 29 at sampling frequency 1000 Hz with and without filtering. Figures 13 and 14 illustrate the comparison of MSEs for different window length without and with filtering. As this figure shows that the wider windows improve the frequency estimation in significantly.

More samples results in better estimation. From the studies reported so far, it was concluded that the filtering effect of the algorithm depends on the processing window length the larger the window, better the frequency characteristics. However, using more samples per data window increases the computation time and speed of the frequency measurement decreases which will slow down the algorithm response.

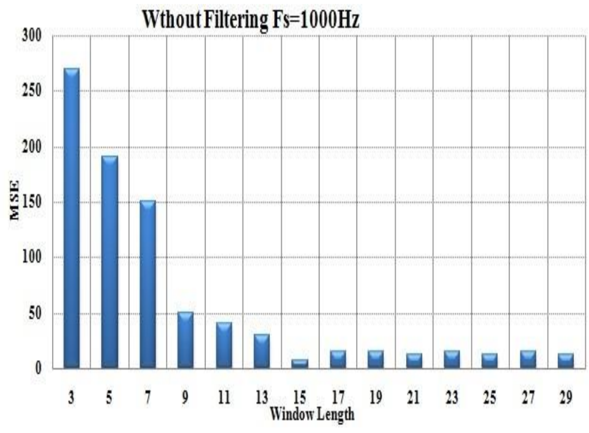

Figure 13. Effect of window length-without filtering f_s = 1000 Hz

B. Sampling Rate

Sampling is the process of converting a continue time signal, such as voltage or current, to a discrete time signal. The sampling rate is usually set as high as is practical considering the capabilities of analog to digital converter and processor. Now discuss the effect of sampling frequency on the algorithm is discussed. For this purpose MSEs are calculated with different sampling frequencies such as 850, 1000, 1200, 2500 and 5000 Hz for case I and case II discussed in previous section.

Figures 15 and 16 depicts the variation of MSEs at different sampling rates with and without filtering for data window of 9. For case I, it is noted that, as the sampling frequency increases from 850 to 5000 Hz, MSEs Increases almost linearly for sampling frequencies less than 1200 Hz and as sampling frequency increases above 1200 Hz, it starts to ascend. For case II MSE is comparable with case I MSEs increases nearly linearly for sampling frequencies less than 2500z and as sampling frequency increases above 2500 Hz, it starts to climb monotonically.

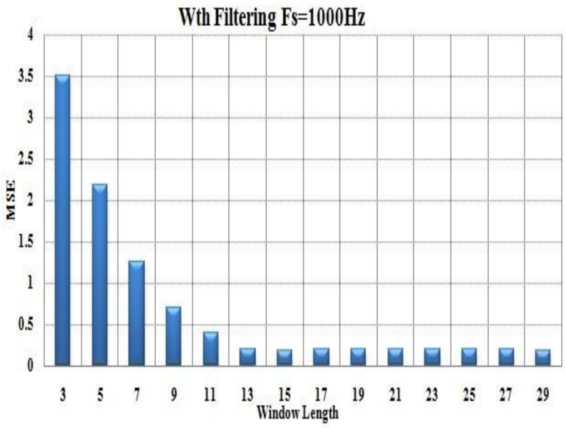

Figure 14. Effect of window length-with filtering f_s = 1000 Hz

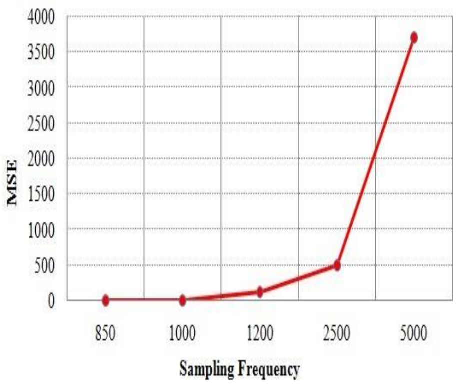

Figure 15. Effect of sampling frequency (Data window size = 9)

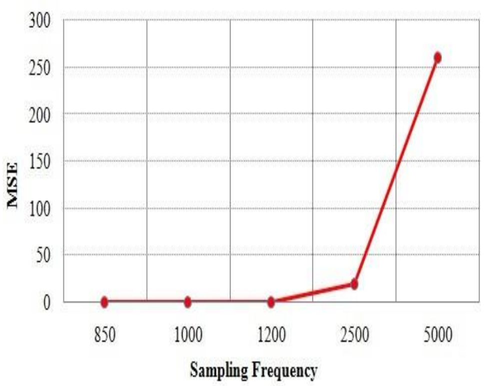

Figure 16. Effect of sampling frequency (Data window size = 9)

VI. CONCLUSIONS

The algorithm for frequency estimation based on proposed least squares method was discussed and tested in laboratory. Experimental results for real time frequency estimation with and without filtering are presented for different sampling rates. Least Squares new approach based real time frequency estimation with filtering, gives the better results as compare to without filtering. For a window size 9, the algorithm has the fast response time. For sampling frequency more than 1200 Hz, increasing sampling frequency degrades the performance of the algorithm; however, filtering improves this degradation. Thus filtering is must. Data window size, sampling rate are the critical parameters which affects the performance of the algorithm. Least squares new approach frequency estimation algorithm provides fast and accurate frequency estimation over a wide range of interested frequency, and the computation requirement is modest for online implementation.

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BIOGRAPHIES

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