A Real-time Study for Frequency Estimation of unbalanced Power System

Dr. Lakshi Prosad Roy[1] Sudipta Chakraborty[2]

[1]Dept. of Electronics and Communication Engineering, NIT-Rourkela, India
Email: royl@nitrkl.ac.in
[2]Dept. of Electrical Engineering, NIT-Rourkela, India
Email: Chakraborty.sudipta02@gmail.com

Abstract— **Estimating the frequency is one of the most important tasks in the power system operation. A least mean square (LMS) algorithm with varying step size to estimate the frequency is studied in this report and its performance under the influence of harmonics, noise, unbalanced conditions, step changes in frequency, etc. is observed through various simulations. Next, Frequency estimation is carried out with improved Non-linear Least Squares (NLS) method in which frequency is estimated through a 1-D search over a specified range. The validity of method under different conditions including line to ground fault is also tested. This method is also verified using the data obtained from an experimental setup consisting of a non-linear load. In this paper an experimental approach of frequency estimation is performed and achieved the aim.**

Index Terms— **Frequency Estimation, Least Mean Square, Non-linear Least Square.**

1. INTRODUCTION

Frequency is the number of cycles per second. It gives the per second power output from stator to rotor (in case of a motor) or from rotor to stator (in case of a generator). In most parts of the world, 50Hz frequency is used while in USA, a frequency of 60Hz is used. But due to technological developments and increasing power demand, frequency is deviated from its nominal value and therefore, there is a need to control the frequency. But to control the frequency, one needs to determine the frequency first. Although it is difficult to accurately determine the frequency, one can estimate the approximate frequency by considering various constraints. Frequency is one of the most important and sensitive parameter of power system. Any variation in power system is eventually reflected in the change of system frequency. A change in frequency leads to a change in system reactance and the operation of several relays such as reactance relays is affected [1]. The electric clocks are driven by synchronous motors whose speed depends on the frequency of the system. Reduced frequency may lead to damage of turbines, stalling of generators, shut down of power plants, damaging of transformers, etc. Frequency is also a measure of mismatch between power generation and load demand. If demand is greater than generation, under-frequency situation arises. If generation is greater than demand, over-frequency situation arises. In either case, change in frequency poses a threat to efficiency and safety of entire system and the chances of collapse of system increase. Thus, Frequency is an integral part of power system protection, power quality monitoring and operation and control of devices using digital technologies. Hence, the accurate estimation and tracking of system frequency is of utmost importance. Due to the development of several electronic and other non-linear devices, the present system is subjected to several undesirable conditions. The system is subject to harmonics, noise, etc. The demand for more and more power is forcing the power systems to operate much closer to their limits and system is prone to several transient and abnormal conditions, noise, harmonics, etc; offline studies are not of much help as every operation needs to be done on the go. Keeping in mind all the undesirable conditions, several methods have been proposed for estimating the frequency online. But all the methods have a trade-off between estimation accuracy, speed of convergence, robustness to noise and sampling rate. In the past forty years, several frequency estimation techniques have been developed with each having its own advantage and disadvantage. Most of these techniques use digitized sample of system voltages. Traditionally, the frequency is estimated by the time between two zero crossings [1] as well as by the calculation of the number of cycles. The voltage waveform was assumed to be pure sinusoid and accordingly, the time between consecutive zero crossings gave the frequency. However, this method fails for distorted signals. Some of the other techniques that have been developed include

1. Variance reduction method [2] in which a stable band-pass second degree digital integrator

(BPSDDI) is used with variance reduction algorithm to estimate the frequency.

2. Orthogonal filters method [3] in which the voltage signal is decomposed into two orthogonal components and using mathematical calculations and simplifications, system frequency is estimated.

3. Kalman filtering [4] which includes both linear and non-linear approaches to accurately estimate the frequency in presence of harmonics and noise.

4. Soft computing techniques like neural network and genetic algorithms are also used for frequency estimation [5, 6].

Among these methods, some methods strictly depend on the performance of filters for filtering out the harmonic content. Some methods are based on the static sinusoid signals and hence, cannot perform well under dynamic conditions while other methods which rely on zero-crossing techniques are unable to perform under unbalanced and fault conditions. Methods are divided into two groups Time domain based approach, like zero-crossing technique and Frequency domain based approach, like Fourier transform. Following sections describe a Least Mean Square (LMS) technique [5] of frequency estimation. It is structurally simple, computationally efficient and robust. Another method employing a 1-D search with a small modification is also discussed. This method is Non-Linear Least Squares (NLS) method. The aim of this paper is

1. To study the Least Mean Square (LMS) technique of frequency estimation and observe its performance under different practical conditions.
2. To study the Non-Linear Least Squares (NLS) technique of frequency estimation and observe its performance under different practical conditions.
3. To modify the NLS technique by overcoming its disadvantages.
4. To validate the modified NLS method by observing its performance under different practical conditions and comparing the results obtained by those of the older NLS method.
5. To acquire data from an experimental setup and observe the performance of the methods.
6. To compare both the linear and non-linear techniques and conclude.

2. LMS METHOD

Three phase voltages can be discredited and represented as [7, 10]

$$V_{ak} = V_m Cos(\omega k \Delta t + \Phi) + \varepsilon_{ak}$$

$$V_{bk} = V_m Cos(\omega k \Delta t + \Phi - 2\pi / 3) + \varepsilon_{bk}$$

$$V_{ck} = V_m Cos(\omega k \Delta t + \Phi + 2\pi / 3) + \varepsilon_{ck}$$

Where V_m= peak value of fundamental component.

ε = noise term.

Δt = sampling interval.

Φ =Phase of fundamental component.

$\omega = 2\pi f$ = Frequency of fundamental signal.

Converting into complex form by $\alpha\beta$ transform

$$\begin{pmatrix} V_{\alpha k} \\ V_{\beta k} \end{pmatrix} = \sqrt{3/2} \begin{pmatrix} 1 & -0.5 & -0.5 \\ 0 & 0.866 & -0.866 \end{pmatrix} \begin{pmatrix} V_{ak} & V_{bk} & V_{ck} \end{pmatrix}^T$$

A complex voltage can be obtained from the above as $V_k = V_{\alpha k} + jV_{\beta k}$

$$V_k = Ae^{j(\omega k \Delta t + \Phi)} + \varepsilon_k$$

$$V_k = \varepsilon_k + \hat{V}_k$$

Where $\hat{V}_k$ is the estimated value of voltage at k^{th} instant. ε_k is the noise component.

Now

$$\hat{V}_k = Ae^{j(\omega k \Delta t + \Phi)} = Ae^{j(\omega (k-1) \Delta t + \Phi)} e^{j\omega \Delta t}$$

$$\hat{V}_k = \hat{V}_{k-1} e^{j\omega \Delta t}$$

$$\hat{V}_k = W_k + \hat{V}_{k-1}$$

This model has 1 input vector element and 1 weight matrix element.

For next iteration

$$\hat{V}_k = W_k + \mu_k e_k \hat{V}_k^*$$

Where * represents the complex conjugate.

μ_{k+1} Is found out by

$$\mu_{k+1} = \lambda \mu_k + \gamma p_k p_k^*$$

Where

$$p_k = \rho p_{k-1} + (1-\rho) e_k e_{k-1}$$

Where $0 < \rho < 1; 0 < \lambda < 1; \gamma > 0$

And $\mu_{\min} < \mu_k < \mu_{\max}$ for better convergence.

At any instant,

$$W_k = e^{j\omega \Delta t} \quad \hat{f}_k = \frac{1}{2\Pi \Delta t} Sin^{-1}[\mathrm{Im}(W_k)]$$

3. NLS METHOD

Any periodic signal can be represented by Fourier series. Assuming the dc component to be zero and the signal *f(t)* is known at *M* uniformly sampled points, we get the following set of *M* equations [11]

$$f(t_k) = \sum_{n=1}^{N} (a_n Cosn\omega_0 t_k + b_n Sinn\omega_0 t_k)$$

Where $k = 0,1,\ldots, M-1$.

We know that waveforms with half-wave symmetry do not contain even harmonics. Also, in three-wire systems, triple harmonics are absent.

Hence $n \in (1,5,7,11,........,n_h)$. Let N_a denote the total number of harmonics present. Then, we can write *f(t)* in matrix notation as follows

H_x= y Here H = [H_a H_b]

H_a=

$$\begin{pmatrix} Cos\omega_0 t_1 & Cos5\omega_0 t_1 & \cdots & Cosn_h\omega_0 t_1 \\ Cos\omega_0 t_2 & Cos5\omega_0 t_2 & \cdots & Cosn_h\omega_0 t_2 \\ \vdots & \vdots & \vdots & \vdots \\ Cos\omega_0 t_m & Cos5\omega_0 t_m & \cdots & Cosn_h\omega_0 t_m \end{pmatrix}_{M\times N_a}$$

$$H_b = \begin{pmatrix} Sin\omega_0 t_1 & Sin5\omega_0 t_1 & \cdots & Sinn_h\omega_0 t_1 \\ Sin\omega_0 t_2 & Sin5\omega_0 t_2 & \cdots & Sinn_h\omega_0 t_2 \\ \vdots & \vdots & \vdots & \vdots \\ Sin\omega_0 t_m & Sin5\omega_0 t_m & \cdots & Sinn_h\omega_0 t_m \end{pmatrix}_{M\times N_a}$$

$$x = \left[a_1\, a_5 \ldots\ldots a_{nh}\ b\, b\ \ldots\ldots\ldots b_{nh}\right]^T_{1\times 2N_a}$$

$$y = \left[\ f(t_1)\, f(t_2) \ldots\ldots f(t_m)\right]^T_{1\times M}$$

Thus, it can be easily seen that minimum number of samples must be equal to 2*Na*. But normally, *M* should be greater than this value for better results. Now, *x* is given by

$x = (H^T H)^{-1} H^T y$

The coefficients and frequency are unknown. We need to estimate only the frequency. The coefficients can be eliminated in the following manner.

$(H^T H)^{-1} H^T y$ = y and the error vector is given by $e = [I - H(H^T H)^{-1} H^T]y$

This error is a function of frequency only. The value of frequency which minimizes the square of error norm is taken to be the estimated frequency. Let

$$[I - H(H^T H)^{-1} H^T]y = A$$

According to the modified NLS method, this A matrix is made to adjust according to the sampling instant. The order of this matrix depends on the number of samples being considered. One cannot go on increasing the samples due to computational and storage considerations. Hence, a window of optimum length is selected to accommodate the required samples. Let the window length be "*Wl*" and sampling frequency be "*fs*" (frequency greater than highest harmonic frequency for proper sampling). So, sampling instant, *t* = 1/*fs* and optimum number of samples, k = *Wl / t* = *Wl * fs*.

This must also be the final size of matrix A. The older method begins to estimate frequency once the minimum number of samples is equal to k. This causes delay. The modified method makes the matrix A a variable one. As a signal is applied, the numbers of samples begin to increase and so are the size of A till its order becomes equal to k. Once this happens; at the next instant, a row of new values is added to A and the row of oldest instant values is deleted, thereby, keeping the order of A at constant value k. Thus, frequency can be estimated with lesser delay.

4. SIMULATION RESULTS

A. SIMULATION RESULTS FOR LMS METHOD

In the MATLAB programming environment with a sampling rate of 5 kHz, different simulations were performed. The values taken were ρ = 0.99, λ=0.97, γ =0.000765, $p_{initial}$=0 and $0 < \mu_k < 0.1$ in each case, the signals assumed are standard 3 phase sinusoidal signals. Estimation of 49.5 Hz signal contaminated by a noise signal with SNR of 40dB we get the response of the method in presence of noise was observed by adding a white Gaussian noise of 40dB to the signal. The filter was initialized at 50Hz with $\mu_k = 0.00445$. It was seen that the frequency was estimated within 0.04 seconds. Estimated frequency = 49.5052 Hz. Error = 0.0052 Hz.

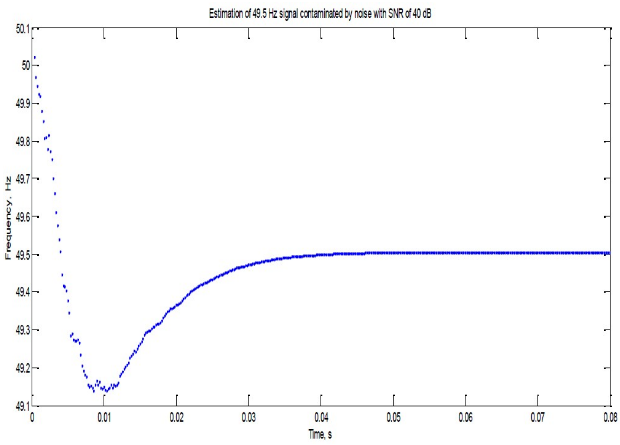


Figure 1. Estimation of 49.5 Hz signal contaminated by noise with SNR of 40dB

Under normal conditions, a 50.5 Hz signal was estimated within 0.04 seconds with $\mu_k = 0.00445$ Estimated frequency = 50.4917 Hz. The signal was initialized at 50 Hz and supplied to the LMS filter. Error in estimation was found out to be around 0.0083 Hz.

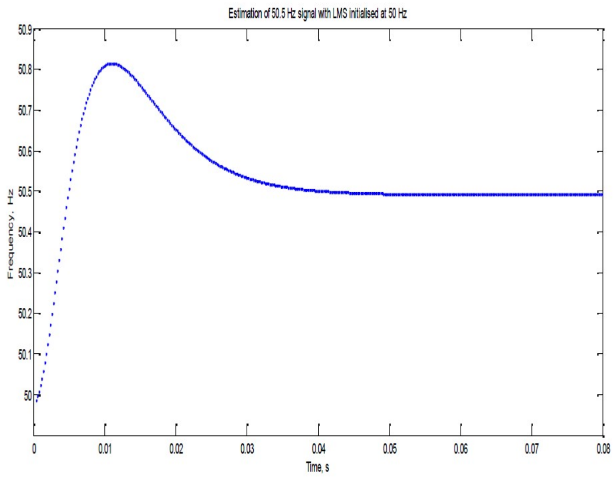


Figure 2. Estimation of 50.5 Hz signal with LMS initiated at 50 Hz

Whenever a frequency change occurs, the voltage signal is affected and so is the performance of the algorithm. The algorithm gave satisfactory results within one cycle when used during sudden frequency jump condition. The frequency was changed from 50 Hz to 48 Hz at 0.0156 s. $\mu_k = 0.00461$ and Estimated frequency = 48.003 Hz.

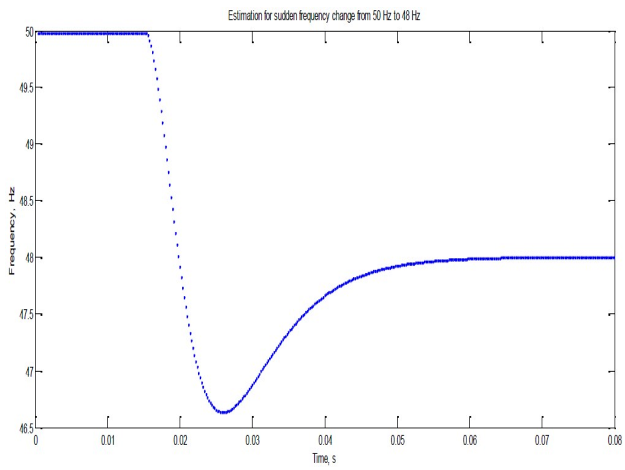


Figure 3. Estimation during a sudden frequency change from 50 Hz to 48 Hz

50 Hz frequency Estimation in presence of 10% 3rd harmonics and 5% 5th harmonics as a results In presence of harmonics also, the frequency was estimated within 0.04 seconds. $\mu_k = 0.00465$ And Estimated frequency = 49.9962 Hz.

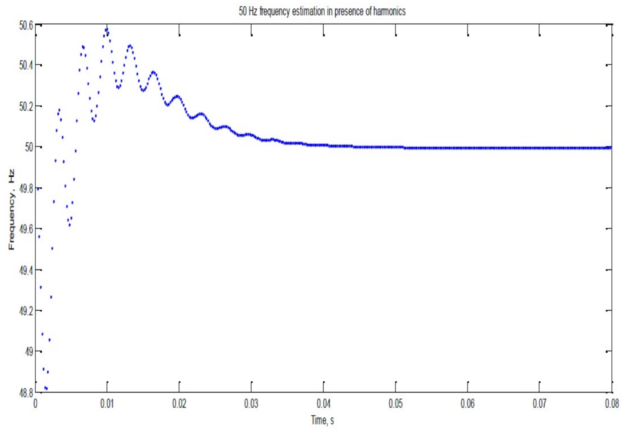


Figure 4. 50 Hz frequency Estimation in presence harmonics

50 Hz frequency estimation during unbalanced condition as a result the voltages of the three phases were made unequal by setting the maximum amplitude to 1.1, 0.9 and 0.8 of each phase respectively. The frequency was then estimated using these signals by LMS algorithm. $\mu_k = 0.0051$ And the frequency was estimated within 0.04 seconds with estimated value being 50.0007 Hz.

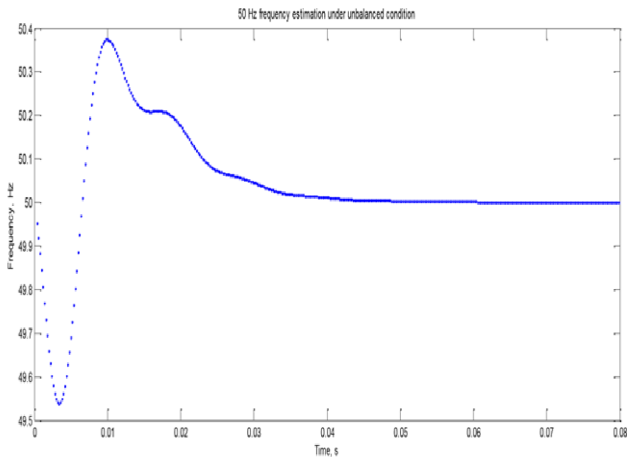


Figure 5. 50 Hz frequency estimation under unbalanced condition

B. NLS METHOD

The signal taken was a pure sinusoidal signal and frequency was varied from 48.5 Hz to 51.5 Hz in steps of 0.1 Hz. The frequency at which minimum norm occurred was the estimated frequency. The sampling frequency was taken to be 1.6 kHz. As is seen from the curve, at 50 Hz, minimum norm occurred and hence, the estimated frequency is 50 Hz which matches with the actual frequency.

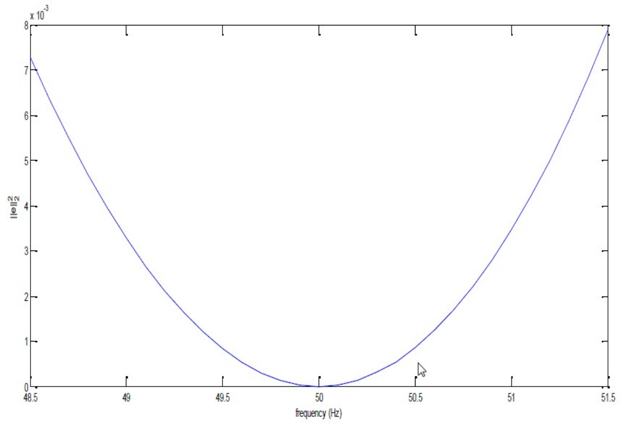


Figure 6. A Simple NLS 1-D Search

Let us consider a signal with 10% THD

$$v(t) = Sin\omega_0 t + 0.0428 Sin7\omega_0 t + 0.0306 Sin11\omega_0 t + 0.0183 Sin13\omega_0 t$$

Let the sampling frequency used be 3.2 kHz and the frequency of this signal be 50 Hz. In the algorithm, the frequency was varied from 48.5 Hz to 51.5 Hz in steps of 0.05 Hz. The frequency which gives the lowest norm is the estimated frequency.

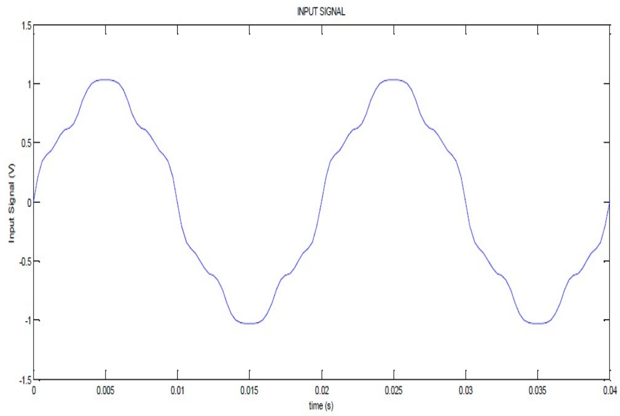


Figure 7. Input Signal with a constant frequency of 50 Hz

A window length of 10ms was used. So, Number of samples per window length = 3.2*10 = 32. Estimation of 50 Hz frequency for a voltage signal of arbitrary peak value as a result a voltage signal of arbitrary peak value was fed to both the algorithms. It was seen that the older method began to estimate frequency only when the number of samples became equal to 32 while the modified method worked independent of the window length and was able to estimate the frequency in 0.005s. It is known that the minimum number of samples required to estimate the frequency must be greater than or equal to two times the number of harmonics present. Here, the assumed signal contains 4 harmonics. So, frequency can be estimated if approx. 10 samples are given. So, the frequency estimation process in modified method begins much earlier.

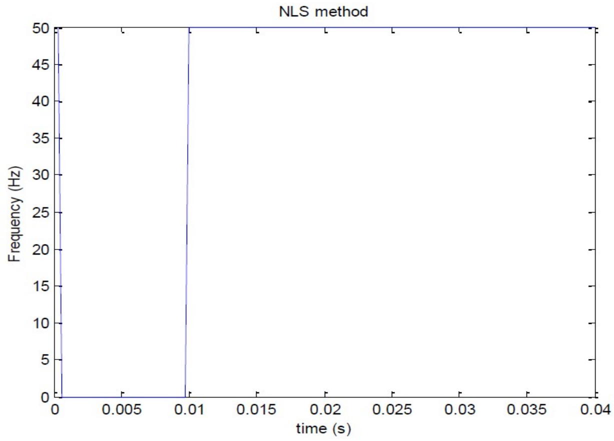


Figure 8. Frequency estimation using old NLS method

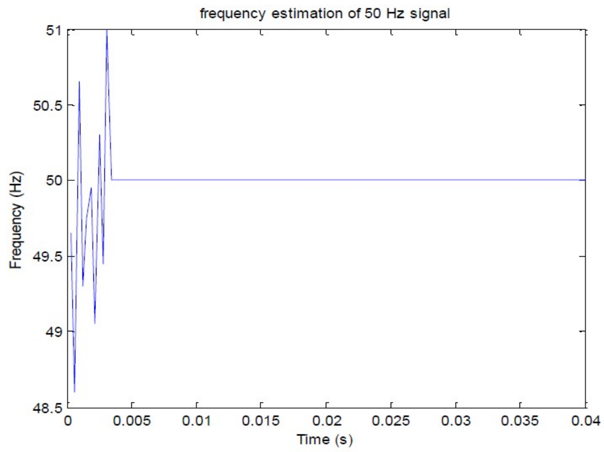


Figure 9. Frequency estimation using modified NLS method

Frequency estimation during frequency jump from 49 Hz to 51 Hz as a result Frequency was suddenly changed from 49 Hz to 51 Hz at 0.02s in the assumed signal. The behavior of both the methods was almost the same in this case.

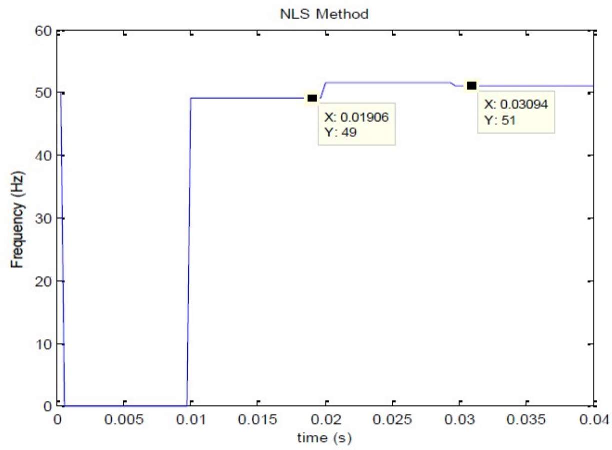


Figure 10. Estimating frequency during frequency jump using old NLS method

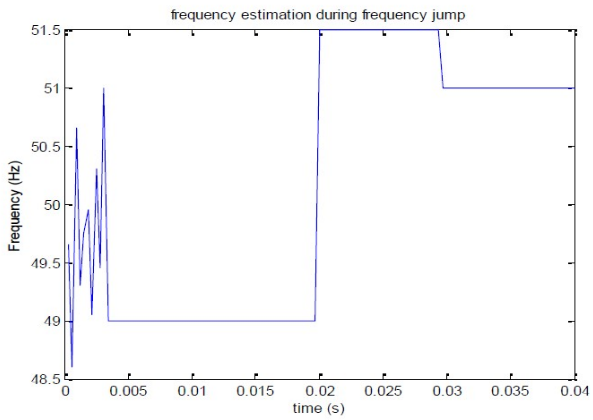


Figure 11. Estimating frequency during frequency jump using modified NLS method

Frequency estimation during 15% step change in magnitude as a result the behavior of both the methods was almost the same in this case. Each of the two methods was able to track the original frequency at a delay equal to the window length.

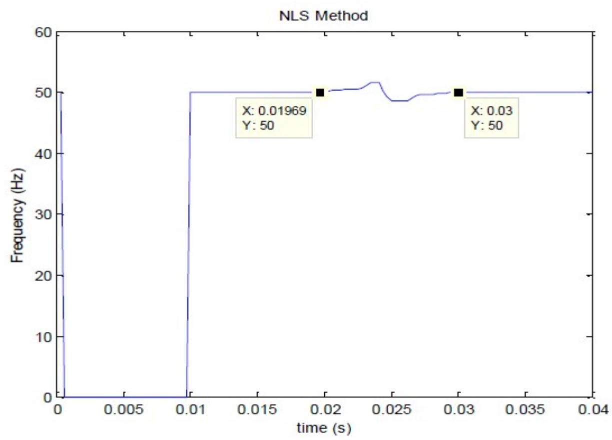


Figure 12. Estimating frequency during magnitude change using old NLS method

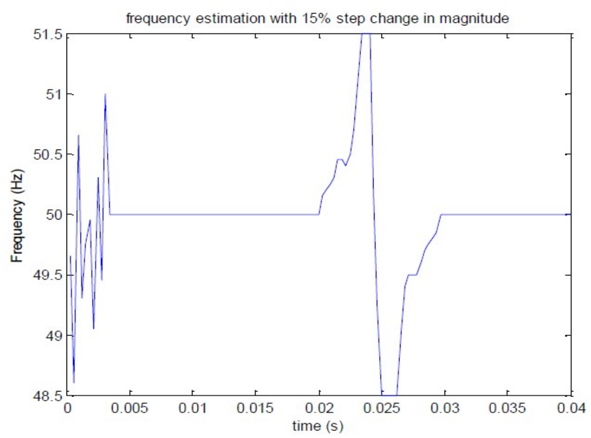


Figure 13. Estimating frequency during magnitude change using modified NLS method

Addition of noise to any signal distorts its waveform and the performance of the algorithm to which the signal is fed may be affected. The performance of both the methods was observed by adding a white Gaussian noise of 60dB to the signal. As a result the modified method was more immune to noise than the older one.

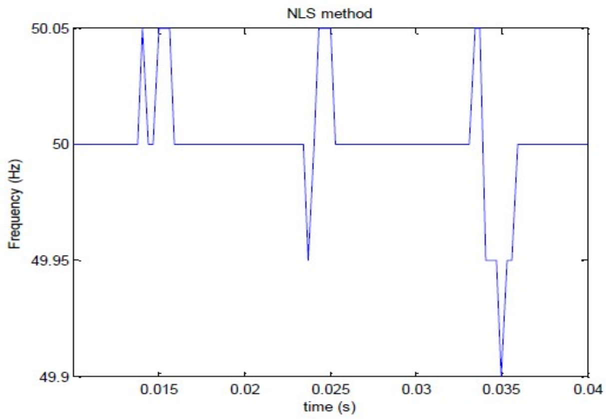


Figure 14. Estimating frequency under noise using old NLS method

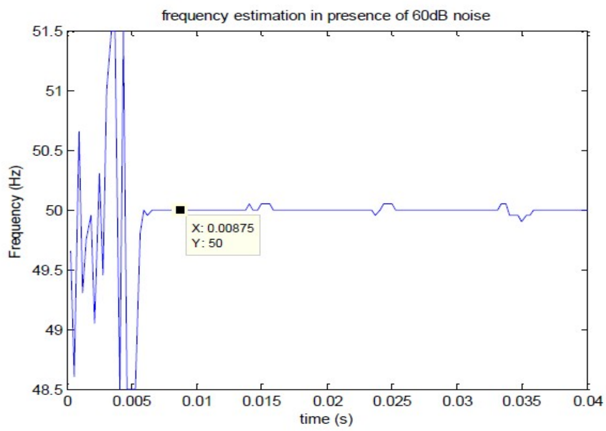


Figure 15. Estimating frequency under noise using modified NLS method

The initial delay in estimating the frequency is independent of the window length in modified method. Whenever there is a frequency jump or step change in magnitude, the time taken to re-estimate the frequency is equal to the window length which is not advantageous if the size of window length is greater because this introduces a delay in estimation process. But a greater window length lowers down the overshoot of frequency in case of magnitude jumps. Also, increasing the window length makes the method more immune to noise.

C. PERFORMANCE OF THE MODIFIED METHOD UNDER FAULT CONDITION

A single line to ground fault was created using PSPICE. The voltage source has a frequency of 50 Hz and peak value of 230V and is supplying an R-L load. An L-G fault occurs at time = 20ms and the system is restored at time = 100ms.

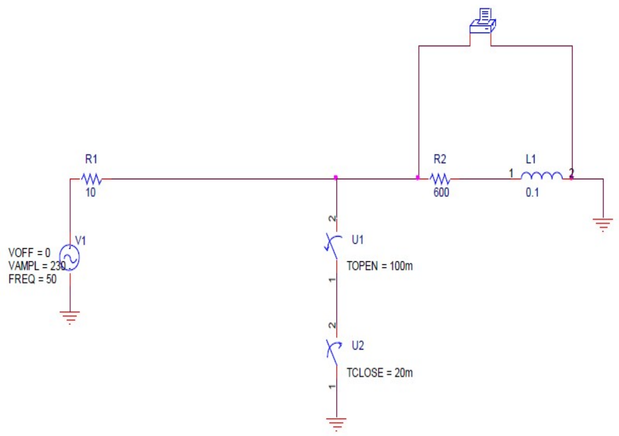


Figure 16. Schematic L-G fault

During the fault, the voltage dips as a result of which the performance of the modified method is affected. During fault, variation in frequency is less when sampling frequency = 6.4 KHz. Also, a fault causes the frequency to dip which is clearly satisfied by this method.

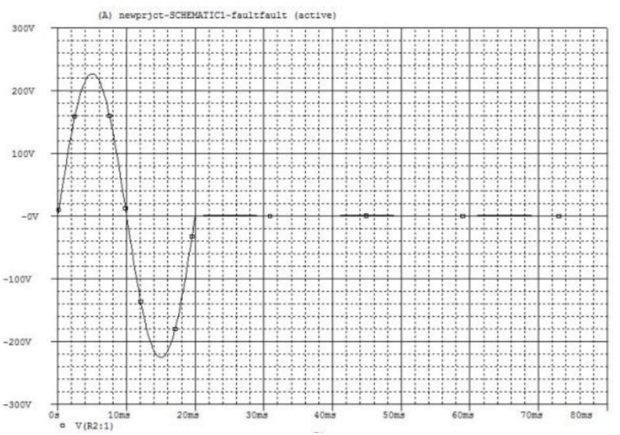


Figure 17. Fault voltage waveform

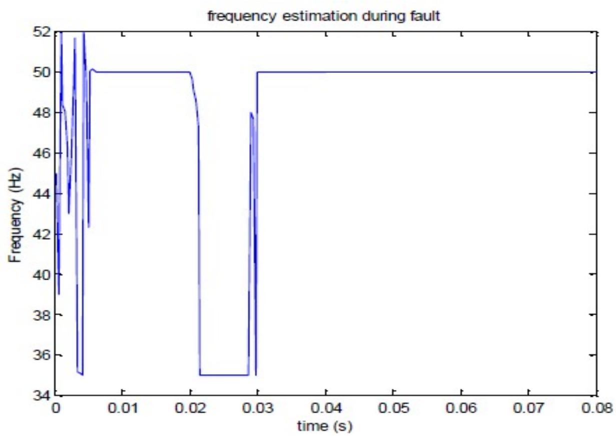


Figure 18. Sampling frequency = 3.2 KHz

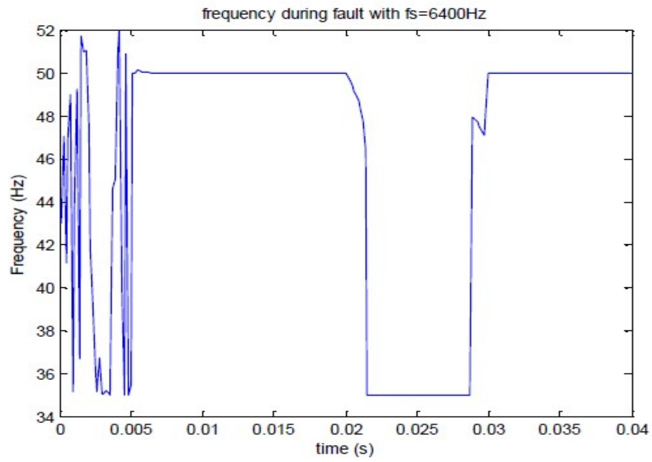


Figure 19. Sampling frequency = 6.4 KHz

5. PERFORMANCE OF THE METHOD UNDER PRACTICAL CONDITION

230 V supply was given to the Auto-transformer input and required voltage was supplied to the R-L load using an Isolation transformer. Rectifier makes the load non-linear and is the source of harmonics because of switching action of diodes. Voltage waveform was taken at the terminals of isolation transformer through a Digital Storage Oscilloscope (DSO) and captured in PC using a PC-PC Communication Software. DSO and PC were connected using a 9-pin female port.

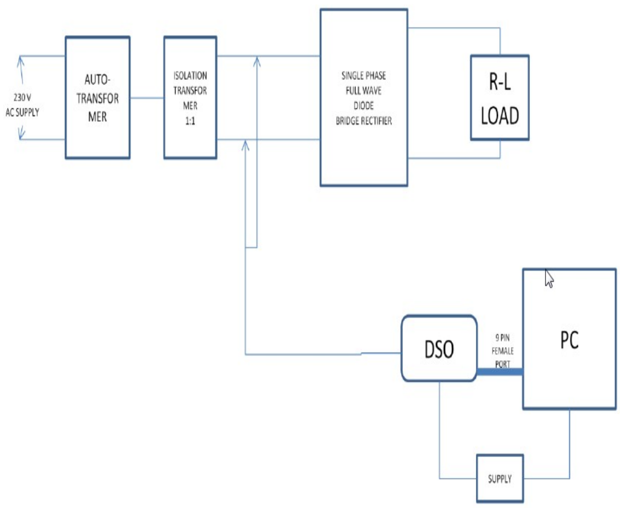


Figure 20. Block Diagram of the Experimental Setup

First set of data

Auto-transformer output = 33V, R=300Ω; L=50mH; frequency=50.1Hz

Second set of data

Auto-transformer output = 120V, R=300Ω; L=250mH; frequency=50.1Hz

For the Simulation,
Sampling Frequency = 5 kHz
Window length for simulation = 30ms
Total data points used = 400 points.
It is observed that the old method takes nearly one and a half AC cycles to estimate the frequency while the modified method estimates the frequency within one AC cycle.

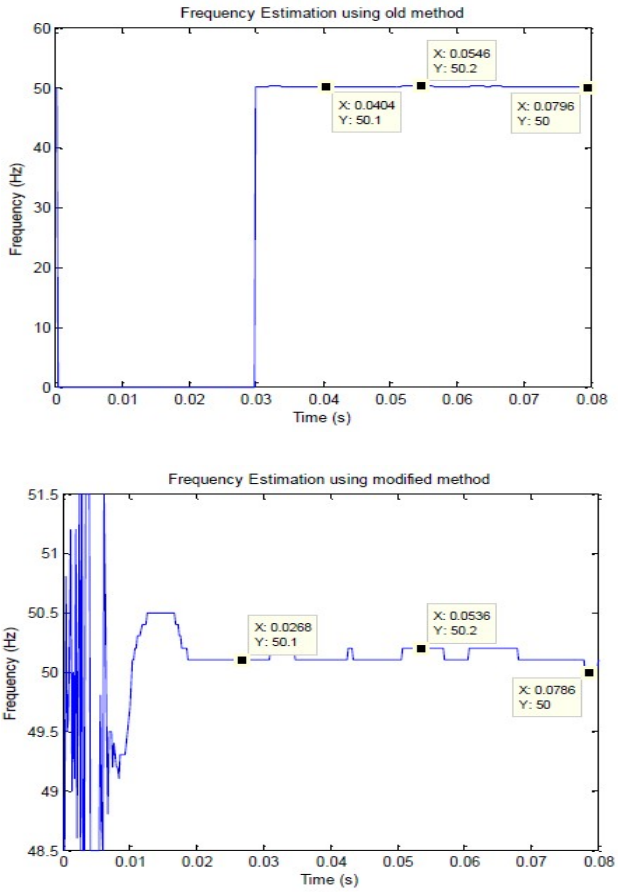
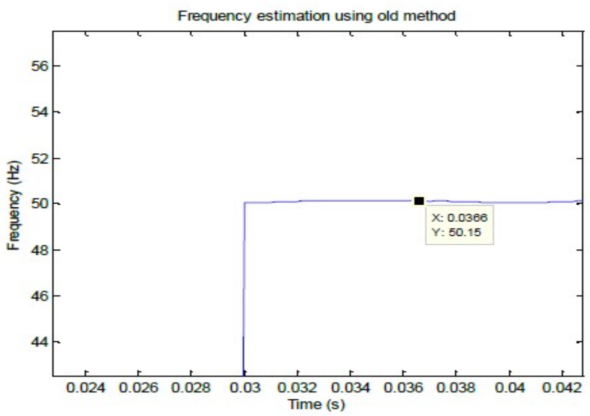


Figure 21. Frequency estimation for the first set of data



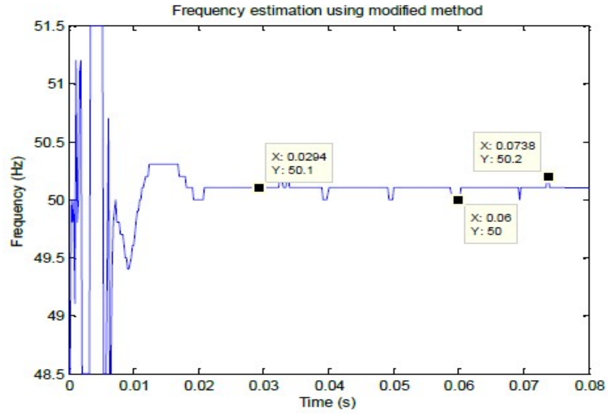


Figure 22. Frequency estimation for the second set of data

It is, thus, quite evident that the modified method estimates the frequency much faster as compared to the old method. In both the methods, frequency oscillation is found to be less than 0.2 Hz in the steady state.

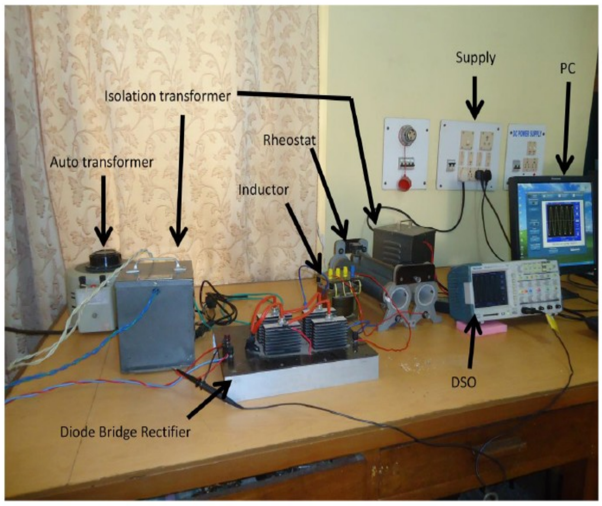


Figure 23. Experimental Setup for Estimation of frequency

Auto transformer Type: 15D-1P
Max. Load = 15A; KVA = 4.05
Input = 240V 50/60Hz; Output = 0-270V

Isolation transformer Capacity = 2KVA
Primary volt = 230 V
Secondary volt = 115 et 115 V

Bridge Rectifier 4 Diodes
25A, 1200V

Rheostat 300Ω, 5A
Inductor 0-250mH (0-50, 0-100, 0-250mH)

DSO Tektronix TPS 2014 (Four channels DSO)
100MHz, 1GS/s
Sampling frequency = 25000Hz

6. CONCLUSION

The performance of modified method under all conditions is satisfactory as compared to the old NLS method and is much better than its linear counterpart, the LMS method although the modified method involved rigorous matrix multiplication and addition. With the modified method, Frequency is estimated within one AC cycle and the frequency oscillations are also very less in the steady state. The modified method holds good for all practical conditions, even during faults with a slight modification in its parameters.

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