International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-8 Issue-11, September 2019

Frequency Estimation of Distorted Signal using Recursive Least Square Filter

Bibhu Prasad Ganthia, Abha Pragati, Sourava Sahoo, Lipsa Ray

Abstract*: *Frequency is an important operating parameter in electrical power system. The operating frequency is not always constant as it varies due to sudden change in generation-load mismatches. In case of load shedding, load- frequency controller requires fast and accurate estimation of frequency. The frequency also influences the functions of different relays. So here the frequency estimation study was performed for the voltage or current signal in presence of noise and disturbances. In this paper Recursive Least Square (RLS) Filter is studied and its frequency estimations are discussed.

Index Terms*: *Adaptive Filters, RLS, LMS, DFT, Frequency Estimation.

I. INTRODUCTION

Frequency plays an important role in electrical power system which is required to be remaining constant because it changes according to the load conditions. Frequency can balance the energy between generation and load. Therefore in practical it is considered as an index parameter. Generally the frequency should be remains constant but due to the presence of noise and disturbances, sudden discrepancy of load-generation and increasing use of non-linear loads it varies. Therefore severe damage or reduction of reactive power occurs due to sudden change in frequency from its desired value. It also affects the functions of different relays in power system. So it plays a vital role in operation and control of any power system devices. Generally digitized voltage signal are used for the estimation of frequency due to less contort than line current. Therefore numbers of techniques are available for estimation of frequency.

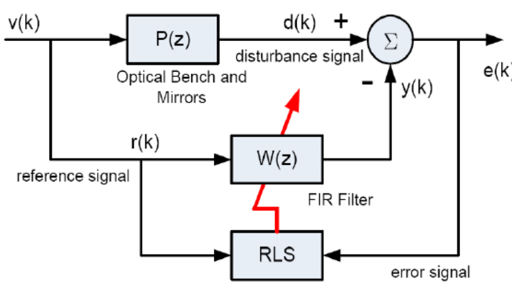

Fig.1. RMS filter with Signalling

Manuscript published on 30 September 2019.
***Correspondence Author(s)**
Bibhu Prasad Ganthia, Assistant Professor, Department of Electrical Engineering, IGIT, Sarang, Dhenkanal, Odisha, India.
Abha Pragati, M.Tech Research Scholar, Department of Electrical Engineering, IGIT, Sarang, Dhenkanal, Odisha, India.
Sourava Sahoo, M.Tech Research Scholar, Department of Electrical Engineering, IGIT, Sarang, Dhenkanal, Odisha, India.
Lipsa Ray, M.Tech Research Scholar, Department of Electrical Engineering, IGIT, Sarang, Dhenkanal, Odisha, India.

In this paper Recursive Least Square (RLS) filtering technique is used for frequency estimation. The section II describes the power system modeling, section III describes about the adaptive filter, section IV explains about the RLS estimation techniques, section V includes the simulation result and section VI concludes the research work.

II. MODELLING OF POWER SYSTEM

The fundamental frequency is the most vital and sensitive parameter in electrical power system. The frequency stability depends on the values of the system frequency. It dynamically varies due to the imbalance between the load and generation. The change in values of the system frequency leads to functional variation of relays. So it is necessary to maintain the frequency in its nominal value. Any deviation in the accuracy of frequency estimation could result in a major grid collapse due to inadequate load shedding. Various methods like time-domain based and frequency-domain based methods have been proposed for estimation of frequency. In this paper adaptive filter is implemented for frequency estimation. A power system voltage or current in discrete time signal can be expressed in the form of

$$y_k = A\cos(k\omega T_s + \phi) + e_k \quad (2.1)$$

Where,
y_k = instantaneous value of signal
A = Amplitude
k = Sampling instant
T_s = Time of sampling
ω = angular frequency
ϕ = phase
e_k = Additive noise
Eq.(2.1) can be written as

$$y_k = \hat{y}_k + e_k \quad (2.2)$$

Where, $\hat{y}_k$ is the estimated signal
The sampled values of the above signal should satisfy the following expression.

$$\hat{y}_k - 2\cos\omega T_s \hat{y}_{k-1} + \hat{y}_{k-2} = 0 \quad (2.3)$$

Now, the problem is to accurately estimate ω from the signal model described in (2.3).

III. ADAPTIVE FILTER

An adaptive filter is a computational device that extracts something desired between two signals having desired and undesired component in real time in an iterative manner. Due to the complexity in the algorithm most of the adaptive filters considered as digital filters. The parameters within this filter structure changes iteratively to alter the input-output relationship. The algorithm associated with this filter describes about adjustment of parameters from one instant to the next.

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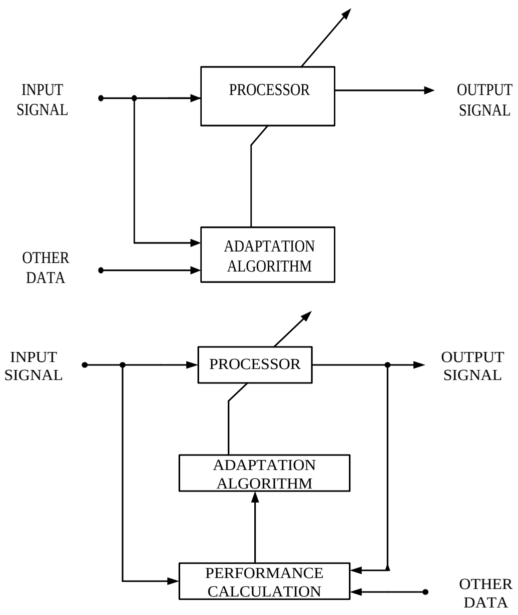

Fig.2. Open Loop Adaptive Filter Structure and Closed Loop Adaptive Filter Structure

In figure no. 2 the adaptive filter block diagram has been drawn which explains how the filter structure associated with input and output signal with adapting the signal error minimization using algorithms of RLS filter.

IV. RECURSIVE LEAST SQUARE (RLS) FILTER

RLS (Recursive Least Square) is an adaptive filter which finds the co-efficient in a recursive manner for the minimization of the weighted least square linear cost functions related with the input signals. In the deviation of the RLS, the deterministic approach is considered for input signals, while in case of LMS and for other similar algorithms they are considered to be stochastic.

A. Block Diagram of RLS Filter

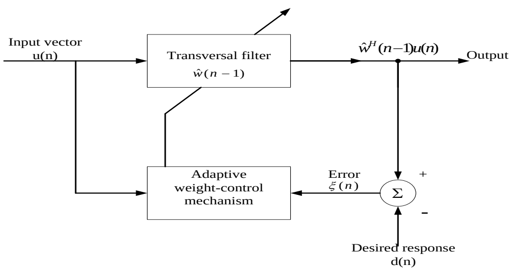

Fig.3. RLS Filter Structure

Compared to other computational techniques, the RLS exhibits extremely fast convergence. The recursive least squares (RLS) algorithm utilizes the input data by extending the instant time at the time of initialization.

B. RLS Adaptation Algorithm

The correlation matrix ϕ(n) should be considered as positive definite and nonsingular. Therefore following identifications should be assumed:

$$A = \phi(n) \quad (4.1)$$

$$B^{-1} = \lambda\phi(n-1) \quad (4.2)$$

$$C = u(n) \quad (4.3)$$

$$D = 1 \quad (4.4)$$

The following recursive equation can be obtained from the inverse of correlation matrix:

$$\phi^{-1}(n) = \lambda^{-1}\phi^{-1}(n-1) - \frac{\lambda^{-2}\phi^{-1}(n-1)u(n)u^H(n)\phi^{-1}(n-1)}{1+\lambda^{-1}u^H(n)\phi^{-1}(n-1)u(n)}$$

(4.2.5)

For convenience of computation, let

$$P(n) = \phi^{-1}(n) \quad (4.6)$$

And

$$k(n) = \frac{\lambda^{-1}P(n-1)u(n)}{1+\lambda^{-1}u^H(n)P(n-1)u(n)} \quad (4.7)$$

$$P(n) = \lambda^{-1}P(n-1) - \lambda^{-1}k(n)u^H(n)P(n-1) \quad (4.8)$$

The P(n) matrix is defined as the inverse of correlation matrix.

We have

$$k(n) = \lambda^{-1}P(n-1)u(n) - \lambda^{-1}k(n)u^H(n)P(n-1)u(n)$$
$$= [\lambda^{-1}P(n-1) - \lambda^{-1}k(n)u^H(n)P(n-1)]u(n)$$

(4.9)

So, we get

$$k(n) = P(n)u(n) \quad (4.10)$$

$$k(n) = \phi^{-1}(n)u(n) \quad (4.11)$$

The gain vector k(n) is defined as input vector u(n) transformed by the inverse of the correlation matrix ϕ(n).

C. Complex RLS-Based Frequency Estimation Algorithm

A distorted noise signal of power system can be given as,

$$y(t) = A_1\sin(\omega_0 t + \emptyset_1) + \epsilon(t) \quad (4.12)$$

To estimate the distorted signal $y(t)$, the angular frequency (ω_0), amplitude (A_1), and phase (ϕ_1) the discretized form the equation (4.3.1) can be expressed as follows:

$$y(k) = A_1\sin(\omega_0 kT)\cos(\emptyset_1) + A_1\cos(\omega_0 kT)\sin(\emptyset_1) + \epsilon(k)$$
$$= [sin\omega_0 kT \quad cos\omega_0 kT][\alpha \quad \beta]^T + \epsilon(k) \quad (4.13)$$

Where, $\alpha = \theta_{11} = A_1 cos\emptyset_1$

$\beta = \theta_{21} = A_1 sin\emptyset_1$

By simplifying equation (1.4.3.2) given in regression form as,

$$y(k) = H(k)\theta + \epsilon(k) \quad (4.14)$$

Here, $\epsilon(k)$ is the noise signal

The following parameters can be obtained by applying the RLS technique. So it can be written as

$$\hat{\theta}(k) = \hat{\theta}(k-1) + K(k)\epsilon(k) \quad (4.15)$$

Where, $\hat{\theta}(k)$= Present estimated value

$\hat{\theta}(k-1)$= Previous estimated value

$K(k)$= Kalman Gain

Therefore measuring error can be obtained as

$$\epsilon(k) = y(k) - H(k)^T\hat{\theta}(k-1) \quad (4.16)$$

The gain K can be updated by using the following equation

$$K(k) = P(k-1)H(k)[\eta I + H(k)^T P(k-1)H(k)]^{-1} \quad (4.17)$$

$P(k)$ is the covariance matrix and η $(0 < \eta > 1)$ is the forgetting factor. Covariance matrix can updated as

$$P(k) = [I - K(k)H(k)^T]\,P(k-1)/\eta \quad (4.18)$$

All the equations from (4.1) to (4.18) are initialized and initial covariance matrix P(0) is taken as $P = \delta I$. Where, I is the identity matrix and δ has large value.

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International Journal of Innovative Technology and Exploring Engineering (IJITEE)
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V. COMPLEX RLS BASED FREQUENCY ESTIMATION ALGORITHM

In power system the three phase voltage signal can be expressed in discretized form as

$$V_{a_k} = V_m \cos(\omega k \Delta T + \emptyset) + \epsilon_{a_k} \qquad (5.1)$$

$$V_{b_k} = V_m \cos\left(\omega k \Delta T + \emptyset - \frac{2\pi}{3}\right) + \epsilon_{b_k} \qquad (5.2)$$

$$V_{c_k} = V_m \cos\left(\omega k \Delta T + \emptyset + \frac{2\pi}{3}\right) + \epsilon_{c_k} \qquad (5.3)$$

Where V_m is peak value of the voltage signal, ϵ_k is the noise component, ΔT is the sampling time, k is the sampling instant, $\emptyset$ is the phase of the signal, and ω is the angular frequency ($\omega = 2\pi f$, with f being the system frequency) [1]. The complex form of signal originated from the three-phase voltages is obtained by $\alpha\beta$ transform written as follows

$$\begin{bmatrix} V_{\alpha_k} \\ V_{\beta_k} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} [V_{a_k} \quad V_{b_k} \quad V_{c_k}]^T \qquad (5.4)$$

A complex voltage V_k can be obtained from above as

$$V_k = V_{\alpha_k} + jV_{\beta_k} \qquad (5.5)$$

Where A is amplitude of the complex signal V_k, and ξ_k is its noise component and $\hat{V}_k = Ae^{j(\omega k \Delta T + \emptyset)}$.

VI. RESULTS AND DISCUSSION

This chapter discusses the MATLAB/Programming software implementation of RLS filter for system identification and frequency estimation.

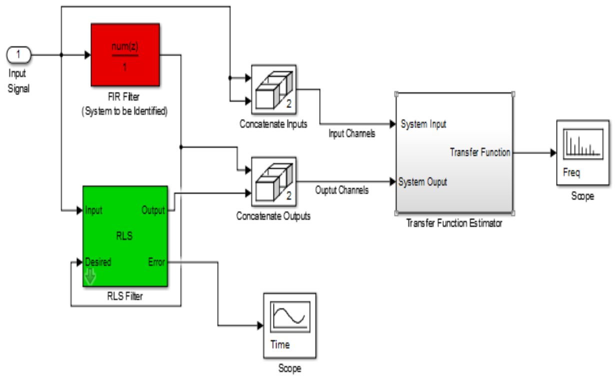

Fig.4. Simulation Diagram of RLS Filter Design

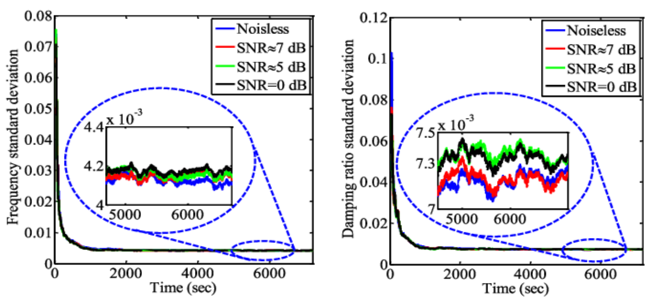

Fig.5. Frequency and Damping Ratio Analysis

RLS Filter for System Identification

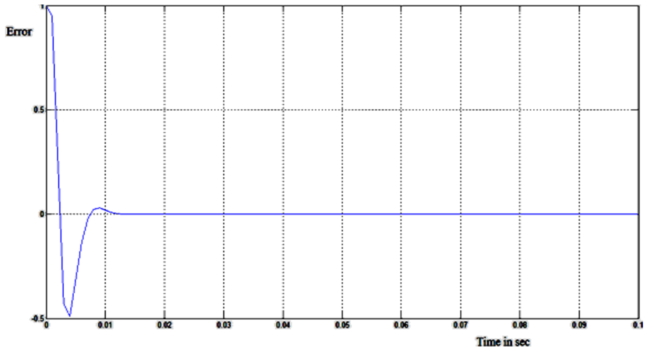

Fig.6. Error waveform of RLS Filter for System identification

For system identification the input x(n) was given as $x = \sin(2\pi f t)$ and the desired input d(n) was given as $d = \cos(2\pi f t)$. Here the RLS filter identified the system after 0.0125 Sec.

Complex RLS Filter for Frequency Estimation

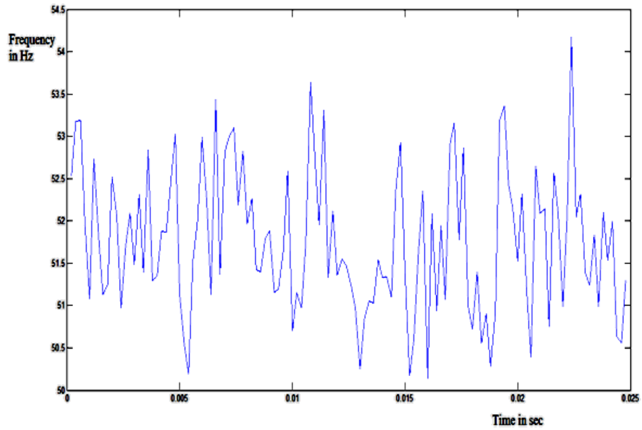

Fig.7. Frequency estimation with the RLS algorithm initialized at 50 Hz

Since here for the estimation of frequency only three samples are used in the RLS Filter it is unable to track any of the frequency i.e. 49.5 Hz and 50.5 H

For System Identification

Table.1. RLS Filter for System Identification

Sl. No.	Filter Type	Time in sec. when the error becomes zero
1	RLS	0.0125

- An algorithm is applied to identify the signal in MATLAB programming environment. At a sampling rate of 1 kHz, systems are identified for RLS Filters. The influencing parameters of the algorithm: $\mu = 0.05, P_{initial} = 0, \lambda = 0.97, \ \gamma = 0.01, and\ \rho = 0.99$.
- For RLS Filters two signals are given to the Filters. They are input signal i.e. $x = \sin(2\pi f t)$ and the desired signal i.e. $d = \cos(2\pi f t)$. Here f is the frequency and the value of the frequency is 50 Hz.

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- Here RLS Filter identified the desired signal after 0.0125 sec. So the RLS Filter converges faster. Due to complexity in RLS Filter we normally use LMS Filter. But for the faster system identification we use RLS Filter.

For Frequency Estimation

- The fundamental frequency can be estimated from the sampled voltage signals by using the algorithm. In the MATLAB programming environment, the sampling rate is found to be 5 kHz. The influencing parameters of the algorithms are $\eta(1) = 0, \delta = 0.01, and\ \lambda = 0.98.$ based on [1].

The algorithm uses only three samples for estimation, which is vulnerable to noise. When $x(n) = 0$, the frequency is undefined and when $x(n)$ is very small, estimation is imprecise. Since here only three samples are used the output shown in figure 4 is not converging.

VII. CONCLUSION

The above algorithm draws the following conclusions of frequency estimation. Here the Recursive least square (RLS) algorithm is used for frequency estimation. The results obtained from the simulation show better rate of convergence than the least mean square approach and also it has good accuracy. Here the system frequency is estimated by using the three phase distorted signal.

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AUTHORS PROFILE

Bibhu Prasad Ganthia is currently working as Assistant Professor in the Department of Electrical Engineering at Indira Gandhi Institute of Technology, Sarang, Odisha, India. He has received his Master's degree in the year 2016 from IGIT, Sarang in Power Electronics & Drives specialization and pursuing his Ph.D at Kalinga Institute of Industrial Technology, Deemed to be University, Bhubaneswar, Odisha, India. He has both teaching as well as industrial experience in his profession. In the short duration he has published 27 journal, book chapters and conference papers in reputed publishers like IEEE, Elsevier and Springer etc. with editor of 3 Scopus index journals and reviewer of many journal and conferences like BEEI, Indonesia, MDPI Journal, IASTER, The Institute of Engineers, Springer etc. He is also the member of national and international scientific associations such as IAENG, SESI, ISRD, IFERP, BEIESP, SCIEI and NSPE and many more. He has software proficiency in MATLAB, ANSYS, LabView, DSpace and VLSI designing. He has got Certificate of Merit for excellence in Mater degree from BPUT, Rourkela, Odisha. He is awarded as "Best Ed Tech Teacher of the Year" by Indian Education Award 2019 sponsored by Techpro Labz and IIT Patna. Moreover he is awarded as "Young Teacher Award" by International School Award 2019, India. He owned Best Researcher Award and Young Researcher Award from DFIRF and Vedant Academics Bangkok Awards in the year 2019 respectively. He has also awarded Innovative Researcher of the Year in renewable energy for the year 2019 by Research Under Literal Access and World Research Council. His Ph.D research is on meta-heuristic artificial neural network optimization, control, protection of wind energy conversion system Hardware-In-Loop in Real Time System.

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Abha Pragati is currently pursuing her M.Tech in Power Electronics & Drives in the Department of Electrical Engineering at Indira Gandhi Institute of Technology, Sarang, Odisha, India. She has received her B.Tech degree in the year 2017 from National Institute of Science & Technology, Berhampur, Odisha in the specialization of Electrical Engineering. Her areas of interest are Power System, Renewable Energy and Machine drives.

Sourava Sahoo is currently pursuing his M.Tech in Power Electronics & Drives in the Department of Electrical Engineering at Indira Gandhi Institute of Technology, Sarang, Odisha, India. He has received his B.Tech degree in the year 2018 from Synergy institute of engineering and Technology, Dhenkanal, Odisha in the specialization of Electrical Engineering. His areas of interest are Power System, Renewable Energy and Power electronics & Drives.

Lipsa Ray is currently pursuing her M.Tech in Power Electronics & Drives in the Department of Electrical Engineering at Indira Gandhi Institute of Technology, Sarang, Odisha, India. She has received her B.Tech degree in the year 2017 from Gandhi Engineering College, Bhubaneswar, Odisha in the specialization of Electrical Engineering. Her areas of interest are Power System, Renewable Energy and Power electronics & Drives.

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