# We are IntechOpen, the world's leading publisher of Open Access books
# Built by scientists, for scientists

**4,800**
Open access books available

**122,000**
International authors and editors

**135M**
Downloads

**154**
Countries delivered to

Our authors are among the
**TOP 1%**
most cited scientists

**12.2%**
Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Chapter 6

# Power System Harmonics Estimation Using Adaptive Filters

Harish Kumar Sahoo and Umamani Subudhi

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.74581

**Abstract**

Accurate estimation and tracking of power quality disturbances requires efficient adaptive model based techniques which should have elegant structures to be implemented in practical systems. Adaptive filters have been used as a popular estimator to track the time-varying power quality events, but the performance is limited due to higher order nonlinearity exists in system dynamics. Harmonics generated in the generation and distribution system are one of the critical power quality issues to be addressed properly. Least mean square (LMS) and recursive least square (RLS) based adaptive estimation models can be used to track the harmonic amplitudes and phases in practical power system applications. Due to time varying nature of harmonic parameters, modifications have to be incorporated in adaptive filters based modeling during estimation of the harmonic parameters and decaying DC components present in the distorted power signals. Volterra expansions can be combined with the adaptive filtering to improve the estimation accuracy and enhance the convergence rate of the estimation model.

**Keywords:** LMS, RLS, Volterra series, decaying DC, power quality

## 1. Introduction

Customers across the globe use large number of power electronic devices that are quite sensitive to power quality (PQ) disturbances in the power network. From the world-wide customer survey, it is found that PQ related issues like voltage dips, voltage swell, transient, harmonics, flicker [1, 2] are increasing every year and these events must be tracked accurately to protect the power networks. Among various PQ problems, harmonics in the network can interact adversely with the utility supply system. Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the supply frequency. Any periodic

IntechOpen

© 2018 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

distorted waveform can be expressed as a sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave. Harmonic distortion is mostly caused by nonlinear characteristics of devices and loads used in a power transmission and distribution network. Adaptive filters are efficient parametric techniques to estimate the harmonic and other PQ parameters accurately. The estimated harmonic parameters can be used to design harmonic elimination filters. Popular harmonic estimation models are based on LMS, NLMS, and RLS family of adaptive filters and the parameters of model are updated in a recursive manner.

## 2. Effects of harmonic distortion

Due to the operation of power electronic devices, harmonic current is produced which give rise to additional harmonic power flow with decreased power factor of the network. Large harmonic current may cause overloading and extra power losses in the network elements. In extreme cases, it can lead to high thermal stresses and early aging of the network devices. Power system equipments such as transformers, cables, motors, capacitors [3] are network components that are mainly affected by harmonic distortion and described in the following sections.

### 2.1. Impact on transformer

Transformer losses are broadly classified into two types as no load losses (Hysteresis and Eddy current loss) and load losses. Among no load losses Eddy current loss varies with square of the frequency and load losses varies with square of the load current. With the presence of harmonic current containing higher frequencies, Eddy current flows in the windings, core and in other conducting bodies causes additional heating. Also because of presence of harmonics, RMS value of current increases such that load losses increases.

### 2.2. Impact on cables

Resistance of a cable depends on skin effect and proximity effect. Due to the presence of harmonics eddy current increases which leads to increase in the effective resistance as well as eddy current losses. Both the effects are dependent on power system frequencies, conductor size, the resistivity and permeability of the material. Due to the presence of harmonics in the cables, the conductor resistance increases and its operating temperature increases further which leads to early aging of the cables.

### 2.3. Impact on capacitor

In the presence of harmonics in the power system, impedance of capacitor decreases with increase in frequency. Due to voltage harmonic present in the power system dielectric losses in the capacitor increases at high operating temperature and reduces the reliability. In extreme situation operational life of capacitor reduces.

http://dx.doi.org/10.5772/intechopen.74581

### 2.4. Impact on motors

Harmonic voltage distortion present at the motor terminals produces harmonic fluxes within the motor such that motor rotates at a frequency different than the rotor synchronous frequency. Presence of harmonic causes additional losses, decreased efficiency, additional heating, vibration and high pitched noise.

Besides the above equipments, presence of harmonics causes interference in communication circuits, overheating of magnetic portions of electrical systems, voltage distortion during resonance. To reduce the effects of harmonics disturbances, harmonic filters must be designed. Before designing the filter, harmonic parameter should be estimated accurately using suitable signal processing method which provides a viable solution to power quality issues.

### 2.5. Causes and effects of decaying DC offset

Electrical signal may contain decaying dc offsets during transient state, performance of discrete Fourier transform (DFT) filter or analog to digital converter (ADC) is improves if DC offset is removed. When short circuit occur, dc offset may appear and normally are of exponential type. The time constant of the component depends on the X/R ratio of the circuit involved in the fault. Hence along with harmonics, decaying dc components has to be estimated and eliminated [3].

## 3. IEEE harmonic standards

The primary objective of standard is to provide regulation for all involved parties to work together to ensure compatibility between customer and service provider. For harmonic limits, standards are governed by IEEE and IEC as described below [1].

### 3.1. IEEE 519

IEEE 519-2009, Recommended Practices and Requirements for Harmonic Control in Electric Power Systems, established limits on harmonic currents and voltages at the point of common coupling (PCC) or point of metering.

The limits of IEEE 519 are intended to:

1. Assure that the electric utility can deliver relatively clean power to all of its customers
2. Assure that the electric utility can protect its electrical equipments from overheating, loss of life from excessive harmonic currents, and excessive voltage stress due to excessive harmonic voltage. Each point from IEEE 519 lists the limits for harmonic distortion at the point of common coupling (PCC) or metering point with the utility. The voltage distortion limits are 3% for individual harmonics and 5% THD.

All of the harmonic limits in IEEE 519 are based on customer load and location on the power system. The limits are not applied to particular equipment, although, with a high amount of nonlinear loads, it is likely that some harmonic suppression may be necessary.

### 3.2. IEEE 519 standard for current harmonics and voltage harmonics

Both end users and utility are responsible for harmonic distortion. According to this standard end users are responsible for limiting the harmonic current distortion and utility will be responsible for limiting harmonic voltage distortion. Distortion standards are based on short circuit capacity (ISC/IL)i.e. ratio of maximum short circuit current at PCC to maximum demand load current at PCC. Both current and voltage distortion limits for each customers are given in **Tables 1–3**.

### 3.3. IEC 61000-3-2 and IEC 61000-3-4 (formerly 1000–3-2 and 1000–3-4)

#### *3.3.1. IEC 61000–3-2 (1995–2003)*

It specifies limits for harmonic current emissions applicable to electrical and electronic equipment having an input current up to and including 16 A per phase, and intended to be connected to public low-voltage distribution systems.

| ISC/IL | h < 11 | 11 ≤ h < 17 | 17 ≤ h < 23 | 23 ≤ h < 25 | h ≥ 35 | TDD (%) |
|---|---|---|---|---|---|---|
| <50 | 2.0 | 1.0 | 0.75 | 0.3 | 0.15 | 2.5 |
| ≥50 | 3.0 | 1.5 | 1.15 | 0.45 | 0.22 | 3.75 |

**Table 1.** Current distortion limits for harmonics.

| ISC/IL | h < 11 | 11 ≤ h < 17 | 17 ≤ h < 23 | 23 ≤ h < 25 | TDD (%) |
|---|---|---|---|---|---|
| <20 | 4.0 | 2.0 | 1.5 | 0.6 | 5 |
| 20–50 | 7.0 | 3.5 | 2.5 | 1.0 | 8 |
| 50–100 | 10 | 4.5 | 4.0 | 1.5 | 12 |
| 100–1000 | 12 | 5.5 | 5.0 | 2.0 | 15 |
| >1000 | 15 | 7.0 | 6.0 | 2.5 | 20 |

**Table 2.** Current distortion limits for harmonics.

| Bus voltage | Individual Vb (%) | THDV (%) |
|---|---|---|
| V < 69 kV | 3.0 | 5.0 |
| 69 ≤ V < 161 kV | 1.5 | 2.5 |
| V ≥ 161 kV | 1.0 | 1.5 |

**Table 3.** Voltage distortion limits for harmonics.

http://dx.doi.org/10.5772/intechopen.74581

| Harmonic order | Maximum permissible harmonic current | Harmonic order | Maximum permissible harmonic current |
|---|---|---|---|
| 3 | 21.6 | 19 | 1.1 |
| 5 | 10.7 | 21 | 0.6 |
| 7 | 7.2 | 23 | 0.9 |
| 9 | 3.8 | 25 | 0.8 |
| 11 | 3.1 | 27 | 0.6 |
| 13 | 2 | 29 | 0.7 |
| 15 | 0.7 | 31 | 0.7 |
| 17 | 1.2 | 33 | 0.6 |

**Table 4.** Harmonic current limits according to IEC 61000–3-4.

### *3.3.2. IEC/TS 61000: 3-4 (1998: 2010)*

It specifies to electrical and electronic equipment with a rated input current exceeding 16 A and up to 75A per phase and intended to be connected to public low-voltage ac distribution systems of the following types:

- Nominal voltage up to 240 V, single-phase, two or three wires
- Nominal voltage up to 600 V, three-phase, three or four wires
- Nominal frequency 50 or 60 Hz

Harmonic current limits based on this standard are shown in **Table 4**.

## 4. Brief literature for adaptive harmonic estimation

Design of robust and efficient harmonic estimation models for accurate estimation of signal parameters in presence of harmonics [4, 5] is a real challenge to power system engineers. Non parametric and parametric estimation models are frequently used to track the harmonic parameters. Non parametric methods are mostly transform based approaches like discrete Fourier transform (DFT) [6], short time Fourier transform (STFT). But these methods suffer from inaccuracies due to system noise and leakage effects. MSDFT proposed by Carugati et al. [7] eliminates the error due to spectral leakage and but still there is limitation during highly non stationary events. Alternately parametric approaches which assumes the signal satisfies a mathematical model with known functional can be used as robust techniques for harmonic estimation. Various parametric methods which include least mean square (LMS) [8], least square (LS) [9, 10], Kalman filters, (KF) [11] are frequently used in power quality monitoring. Among various adaptive filters, LMS has simple structure and offers good convergence behavior in case of stationary signal. But it provides poor estimation performance owing to its poor convergence rate when the signal statistics are time varying. In case of RLS and KF, initial choice of covariance matrix is difficult for faster and stable convergence of the algorithm. To improve the error convergence property, Volterra expansion [12, 13] of the input samples is incorporated to develop robust adaptive filter in this chapter. LMS/F [14] filter is developed as a compromise between LMS and LMF [15] which is further extended by the use of Volterra series expansion to develop Volterra LMS/F filter. RLS filter also can be combined with Volterra series to develop Volterra RLS filter with faster convergence. The efficiency of all these filters can be tested for harmonic estimation using performance measures like estimation error, mean square error (MSE) etc.

## 5. Adaptive algorithms for harmonic estimation

Different adaptive algorithms for harmonic estimations are described in the following sections.

### 5.1. LMS algorithm for harmonic estimation

Least mean square (LMS) algorithm was originated by Window and Hoff (1960). LMS filter is simple to implement which involves processes like

**a.** A filtering process which involves computation of the output of a linear filter in response to an input signal and generates an estimation error by comparing this output with a desired response.

**b.** An adaptive process which involves the automatic adjustment of the parameters of the filter in accordance with the estimation error.

**Steps to implement LMS algorithm:**

- Initialize weight vector $w$
- Generate power signal
- Discretize the power signal with the desired sampling frequency meeting Nyquist criteria and estimate the signal using initial state vector
- Calculate the estimation error

Update the weight vector as-

$$\hat{w}(n) = \hat{w}(n-1) + \mu e(n-1)x(n-1) \tag{1}$$

where $\mu$ is the step size

- Go to step 4 if last iteration is not obtained
- Estimate amplitudes and phases of fundamental and harmonics using Eq. (24-27).

  The step size parameter $\mu$ convergence in mean square given by

$$0 < \mu < \frac{1}{MS_{\max}} \tag{2}$$

where M is the length of the filter in terms of tap weights and $S_{max}$ is the maximum value of the power spectral density of the tap inputs. This algorithm requires only 2 M + 1 complex multiplications and 2 M + 1 complex addition per iteration.

### 5.2. Recursive least square (RLS) for harmonic estimation

Recursive least square (RLS) is the recursive implementation of least square in which computation is started with prescribed initial conditions and use the information contained in new data samples to update the old estimates. The cost function to be minimized is given by:

$$\xi(n) = \sum_{i=1}^{n} \beta(n,i)|e(i)|^2 \tag{3}$$

where n is the variable length of the observable data; $\beta(n,i)$ is the weighting factor satisfying the property

$$0 < \beta(n,i) \leq 1, i = 1, 2.....n \tag{4}$$

The use of weighting factor is intended to ensure that data in the distance past are forgotten in order to afford the possibility of following statistical variation of the observable data when the filter operates in a non stationary environment. A special form of weighting is commonly used known as forgetting factor and is defined by:

$$\beta(n,i) = \lambda^{n-i} \qquad i = 1, 2....n \tag{5}$$

where $\lambda$ is a positive constant close to but less than unity.

**Steps to implement RLS algorithm:**

- Initialize weight vector and inverse correlation matrix

$$\mathrm{W}(0) = 0, P(0) = \delta^{-1}I \tag{6}$$

where $\delta$ is small positive constant for high SNR and large positive constant for low SNR.

- Generate the discretized form of power signal using the corresponding sampling frequency.
- Calculate the estimation error.
- Update the weight vector as

$$\hat{w}(n) = \hat{w}(n-1) + k(n)e(n) \tag{7}$$

where the relation between gain k with covariance parameter vector is

$$k(n) = \frac{\pi(n)}{\lambda + X^T(n)\pi(n)} \tag{8}$$

and

$$\pi(n) = P(n-1)X(n) \tag{9}$$

- Using matrix inversion lemma, the updated covariance matrix is given as

$$P(n) = \lambda^{-1}P(n-1) - \lambda^{-1}k(n)X^T(n)P(n-1) \tag{10}$$

- Amplitude and phases of fundamental and harmonic parameters as well as decaying dc components are estimated using Eq. (24)

## 6. Volterra series

Volterra series is an expansion applied to input vector for analysis of non-linear behavior of the system and the expanded patterns are the inputs to the adaptive estimation model as shown in **Figure 1**.

A continuous time-invariant system with x(t) as input and X(t) as output can be expanded through Volterra series as

$$X(t) = \left[x(t)\;\; x(t-1)\ldots x(t-M)\;\; x^2(t)\ldots x^2(t-M)\;\; \ldots\ldots\ldots\;\; x(t)x(t-1)\right] \tag{11}$$

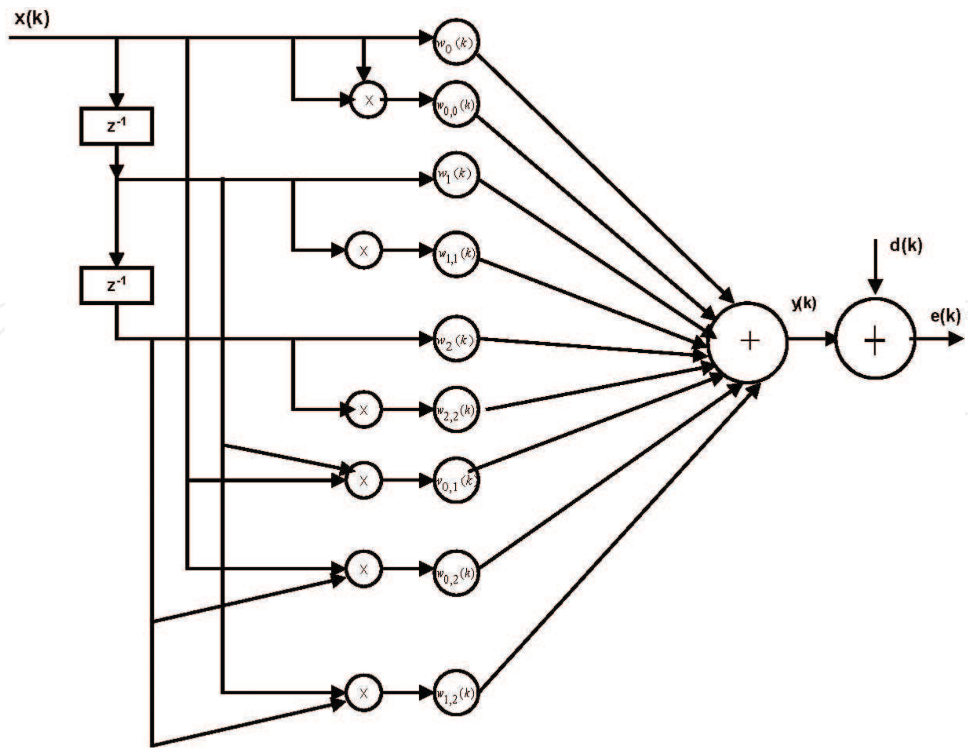


**Figure 1.** Structure of Volterra filter.

Volterra structure can be combined with LMS, LMF, RLS to construct new kind of adaptive filters such as Volterra LMS, Volterra LMF and Volterra RLS etc.

### 6.1. Volterra LMS/F algorithm for harmonic estimation

LMS Algorithm is the simplest algorithm which is easy to implement. Since the convergence property degrades in case of non stationary signal, Walach & Widrow [15] applied the fourth order power optimization area. However the computational complexity of LMF is very high. A combined approach known as LMS/F algorithm proposed by Harris [17] considering the trade-off between convergence speed and steady state performance. Further reduction of convergence speed is achieved by using Volterra series expansion of input samples to develop a robust adaptive filter known as Volterra LMS/F filter [16].

**Steps to implement VLMS/F algorithm:**

- Initialize weight vector
- Generate expanded input vector using Volterra expansion
- Generate error signal vector using difference of desired and output signal vector

Updated weight vector can be evaluated as:

$$\hat{w}(n) = \hat{w}(n-1) + \mu \frac{e^3(n-1)}{e^2(n-1)+\alpha} x(n-1) \tag{12}$$

where $\mu$ is the step size and $\alpha$ is the threshold parameter. They are used to trade off between convergence and steady state performance.

### 6.2. Volterra RLS algorithm for harmonic estimation

To enhance the convergence speed of RLS filter, input signal vector is expanded to higher dimensions using Volterra series expansion. As a result a new filter came up known as Volterra RLS filter.

Steps to implement Volterra RLS Algorithm:

- Initialize weight vector and inverse correlation matrix
- Generate expanded input vector using Volterra expansion
- Generate error signal
- Inverse correlation matrix is updated as

$$P(n) = \lambda^{-1}P(n-1) - \lambda^{-1}k(n)X^T(n)P(n-1) \tag{13}$$

- Estimate the updated weight vector as:

$$\hat{w}(n) = \hat{w}(n-1) + k(n)e(n) \tag{14}$$

## 7. Harmonic estimation model

Assuming voltage or current waveforms of power signals with higher order harmonics corrupted by noise, the general form of the waveforms can be expressed as [16].

$$z(t) = \sum_{n=1}^{N} A_n \sin\left(\omega_n t + \phi_n\right) + a_{dc} e^{-\alpha_{dc} t} + v(t) \tag{15}$$

where $\omega_n = n2\pi f_0$ and $f_0$ is the fundamental frequency, N is the number of harmonics, $v(t)$ is the additive white Gaussian noise, $a_{dc}e^{-\alpha_{dc}t}$ is the decaying dc component.

The discrete version of Eq. (15) can be represented as:

$$z(k) = \sum_{n=1}^{N} A_n \sin\left(\omega nkT_s + \phi_n\right) + a_{dc} e^{-\alpha dckTS} + v(kTs) \tag{16}$$

where $T_s$ is the sampling period.

Decaying DC component can be approximated for smaller value of '$\alpha_{dc}kT_S$' as

$$a_{dc} e^{-\alpha_{dc} kT_S} \simeq a_{dc}(1 - \alpha_{dc} kT_S) \tag{17}$$

Using Eq. (17) in Eq. (16) $z(k)$ can be obtained as:

$$z(k) = \sum_{n=1}^{N} A_n \sin\left(w_n kT_s + \phi_n\right) + a_{dc} - a_{dc}\alpha_{dc} kT_s + v(kT_s) \tag{18}$$

For estimation of amplitudes and phases Eq. (18) can be rewritten as

$$z(k) = \sum_{n=1}^{N} \left[A_n \sin\left(\omega_n kT_s\right) \cos\phi_n + A_n \cos\left(\omega_n kT_s\right) \sin\phi_n\right] + a_{dc} - a_{dc}\alpha_{dc} kT_s + v(kT_s) \tag{19}$$

Eq. (19) can be expressed in parametric form as:

$$z(k) = X(k) w^T(k) \tag{20}$$

Thus input signal vector can be expressed as

$$x(k) = [\sin\left(\omega_1 kTs\right) \quad \cos\left(w_1 k\omega Ts\right)\ldots \ \sin\left(\omega_N kTs\right) \quad \cos\left(\omega_N kTs\right) \ \ 1 \quad -kT_s] \tag{21}$$

The vector of unknown parameter is expressed as:

$$w(k) = [w_1(k) \ \ w_2(k)\ldots w_{2N}(k) \ \ w_{2N+1}(k) \ \ w_{2N+2}(k)] \tag{22}$$

$$w(k) = \left[A_1 \ \cos\phi 1 \ \ A_1 \ \sin\phi 1\ldots A_n \cos\phi_n \ \ A_n \sin\phi_n \ \ a_{dc} \ \ a_{dc}\alpha_{dc}\right] \tag{23}$$

Amplitude and phase estimation can be carried out with updated coefficients of filtering algorithms as given below.

$$\hat{A}_n = \sqrt{\hat{w}_{2N}^2 + \hat{w}_{2N-1}^2} \tag{24}$$

$$\hat{\phi}_n = \tan^{-1}\left(\frac{\hat{w}_{2N}}{\hat{w}_{2N-1}}\right) \tag{25}$$

$$a_{dc} = w_{2N+1} \tag{26}$$

$$\hat{\alpha}_{dc} = \tan^{-1}\left(\frac{\hat{w}_{2N+2}}{\hat{w}_{2N+1}}\right) \tag{27}$$

## 8. Simulation results

### 8.1. Case-1

For estimation of harmonics using VLMS/F algorithm, balanced voltage signals across any one phase can be expressed as

$$z(k) = 1\sin(k\omega Ts + \pi/6) + 0.5\sin(3k\omega Ts + \pi/3) + 0.3\sin(5k\omega Ts + \pi/4) + 0.2e^{-8kTS} \tag{28}$$

To test the performance of the proposed algorithm, comparison plots are presented from **Figures 2–7**. These figures include amplitude and phase estimation results of fundamental, third and fifth harmonic components. The results clearly indicate that VLMS/F filter has a faster tracking capability as compared to other algorithms. The decaying DC component is also included along with harmonics up to 5th order. Decaying DC amplitude estimation comparison plot is presented in **Figure 8**. It is observed that VLMS/F algorithm tracks the decaying DC component accurately than other algorithms. Absolute estimation comparison

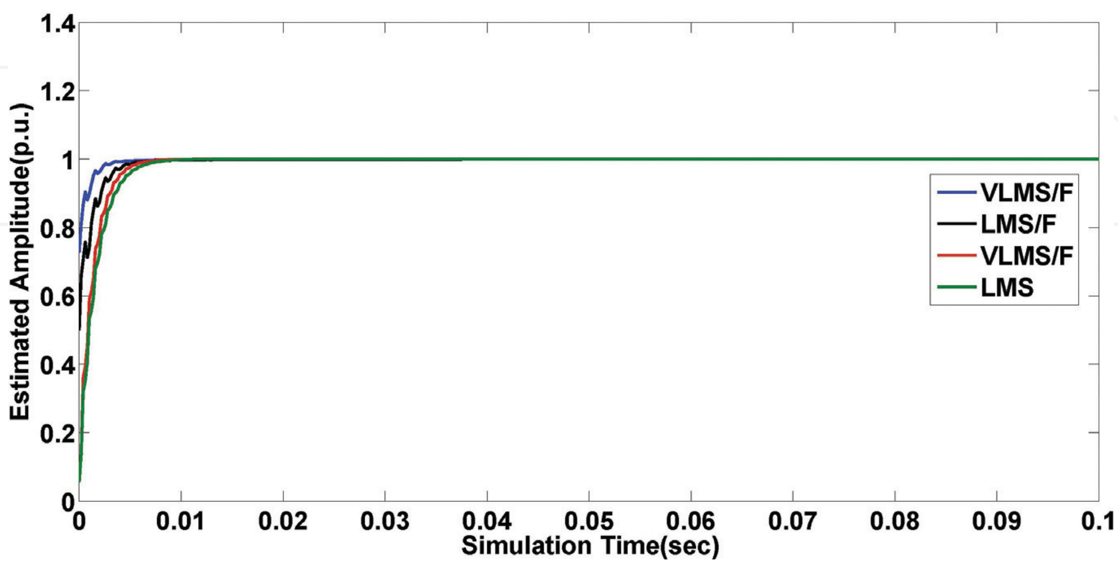


**Figure 2.** Comparison results of fundamental amplitude.

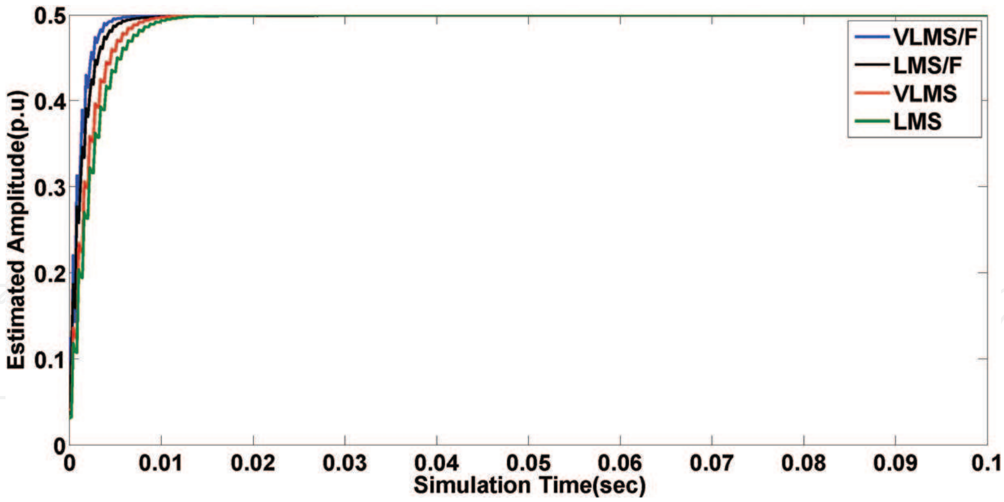


**Figure 3.** Comparison results of third harmonic amplitude.

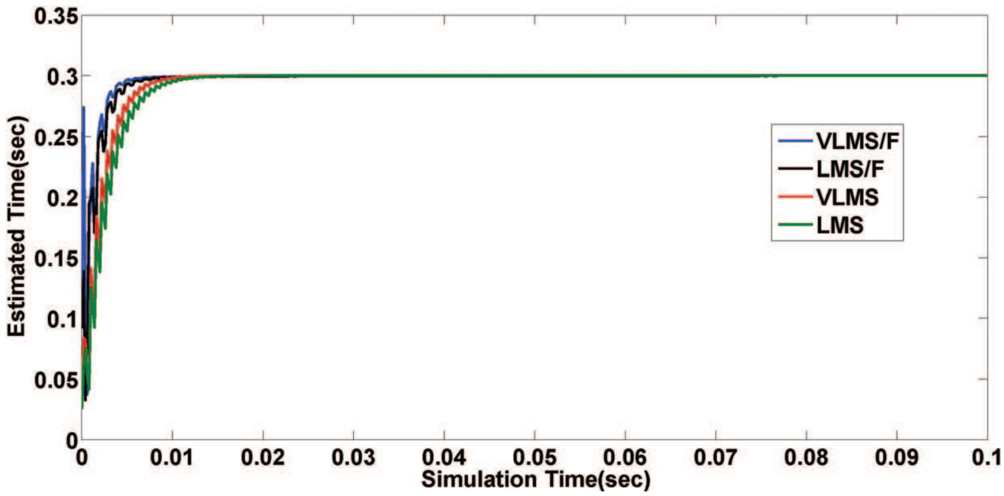


**Figure 4.** Comparison results of fifth harmonic amplitude.

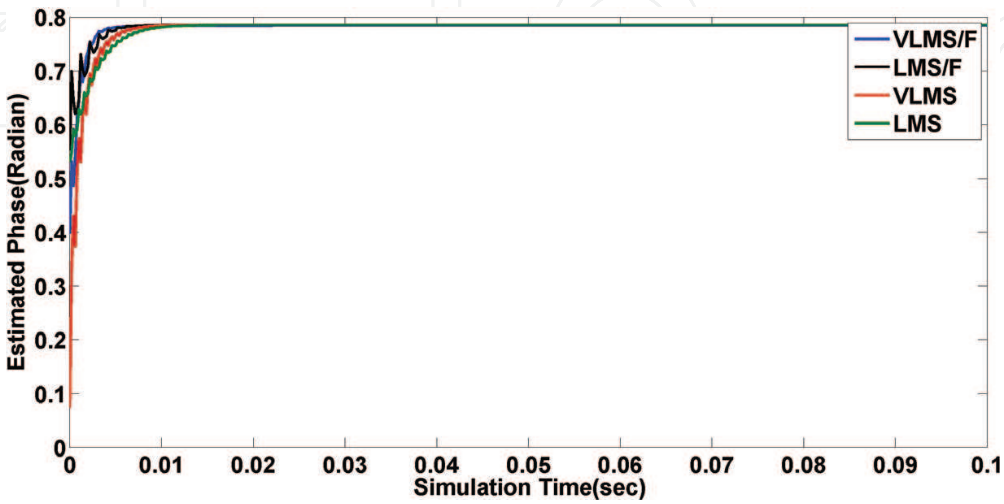


**Figure 5.** Comparison results of fundamental phase.

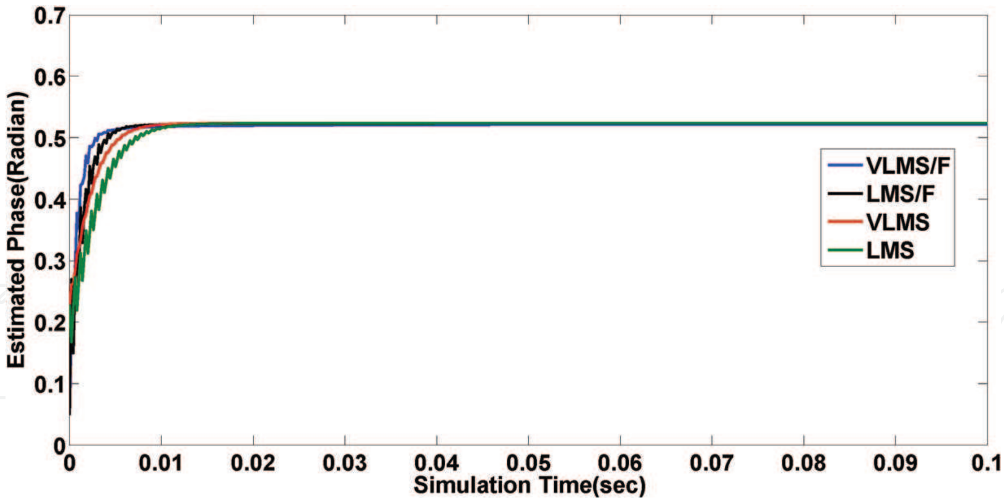


**Figure 6.** Comparison results of third harmonic phase.

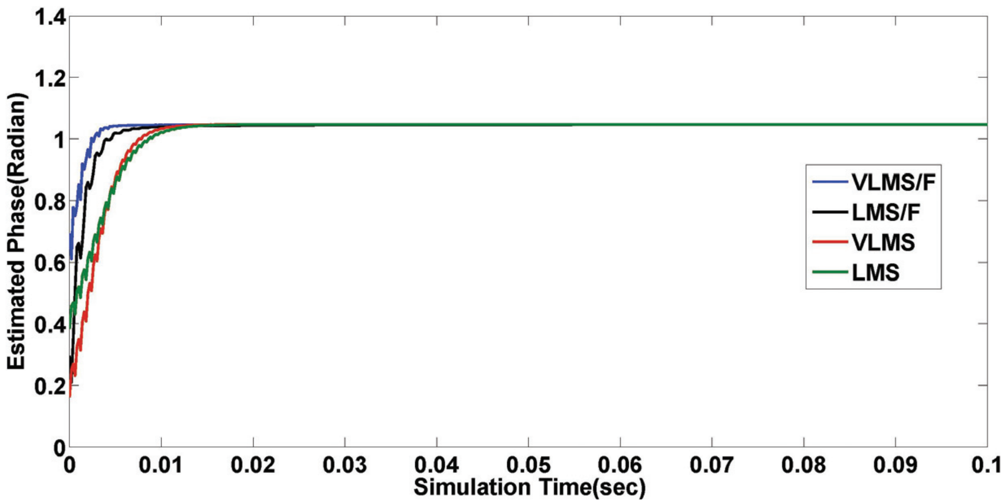


**Figure 7.** Comparison results of fifth harmonic phase.

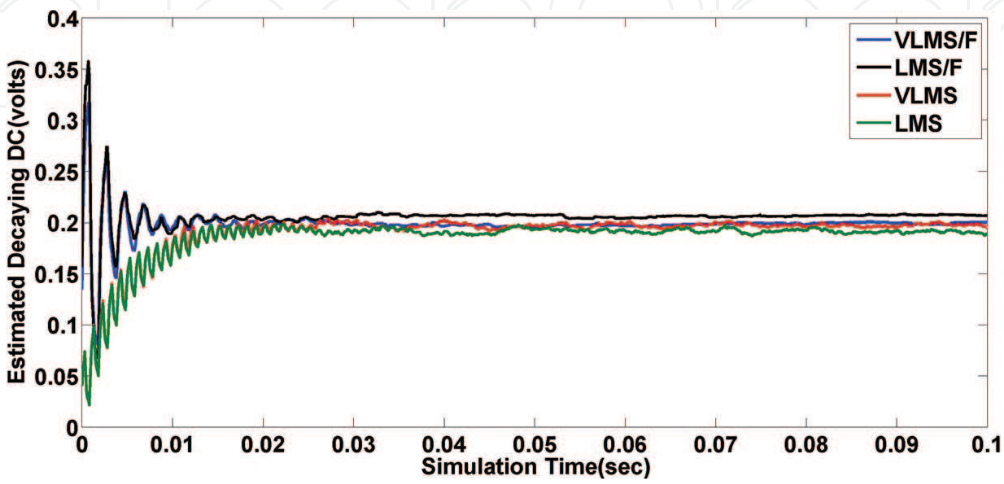


**Figure 8.** Comparison results of decaying DC amplitude.

| Algorithms | Absolute estimation error | | | | | | |
|---|---|---|---|---|---|---|---|
| | Fundamental amplitude | Third harmonic amplitude | Fifth harmonic amplitude | Fundamental phase | Third harmonic phase | Fifth harmonic phase | Decaying DC |
| LMS | 0.0004383 | 0.002437 | 0.002505 | 0.001066 | 0.001251 | 0.00561 | 0.1218 |
| Volterra LMS | 0.0005238 | 0.002398 | 0.002328 | 0.001007 | 0.001181 | 0.005481 | 0.05339 |
| LMS/F | 0.16 | 0.004827 | 0.003253 | 0.0007725 | 0.0003231 | 0.006877 | 0.007843 |
| VLMS/F | 0.1599 | 0.004803 | 0.003209 | 0.0008388 | 0.0002715 | 0.006571 | .07727 |

**Table 5.** Estimation error comparison results.

results are shown in **Table 5**. It is observed that performance of VLMS/F is better as compared to other algorithms.

### 8.2. Case-2

For estimation of harmonics using VRLS algorithm, balanced voltage signals across any one phase can be expressed is as

$$z(k) = 1.2\sin(k\omega Ts + \pi/6) + 0.8\sin(3k\omega Ts + \pi/3) + 0.3\sin(5k\omega Ts + \pi/4) \tag{29}$$

All the simulations are performed using MATLAB Simulink environment. For LMS and VLMS, step size is chosen as 0.001. For FFRLS and VRLS, 0.9995 is chosen as forgetting factor for simulation. Additive white Gaussian noise with 30 dB SNR and sampling frequency of 2 KHz are considered during estimation of harmonics. Estimated amplitude and phase comparison plots of fundamental, third and fifth harmonics are presented from **Figures 9–14**. From the harmonic estimation plots it is clear that LMS and VLMS have slower convergence as compared to FFRLS and VRLS.

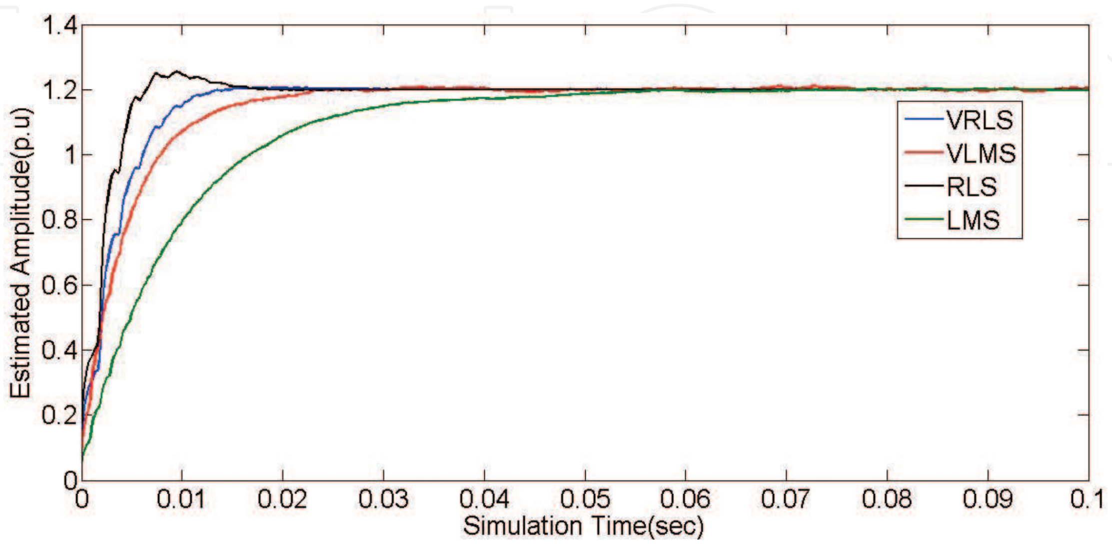


**Figure 9.** Comparison results of fundamental amplitude.

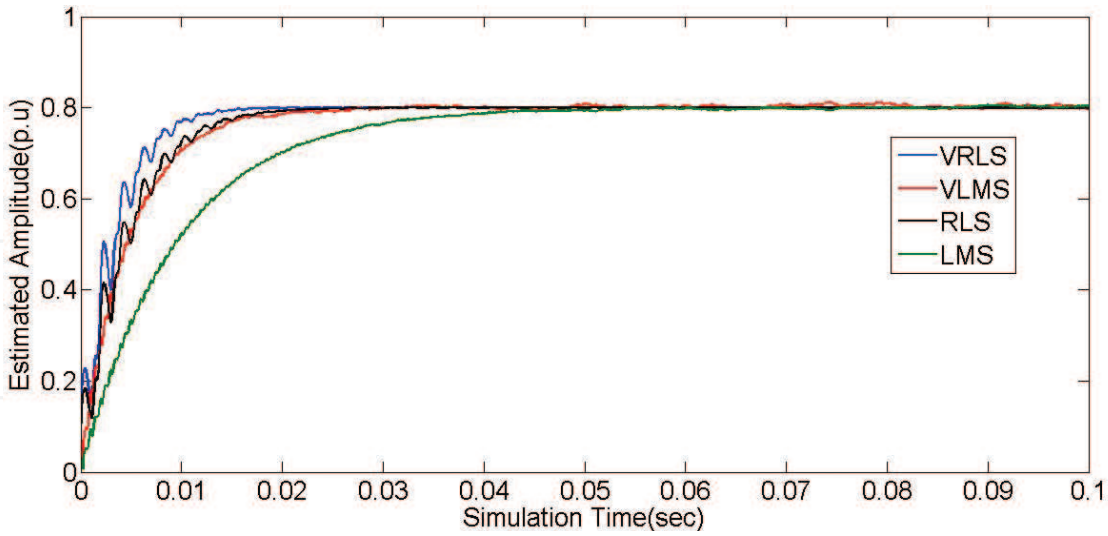


**Figure 10.** Comparison results of third harmonic amplitude.

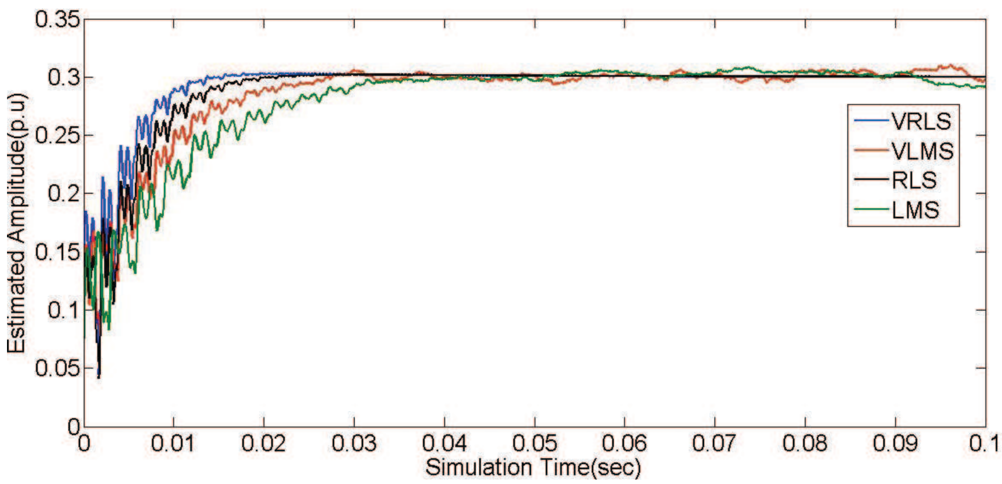


**Figure 11.** Comparison results of fifth harmonic amplitude.

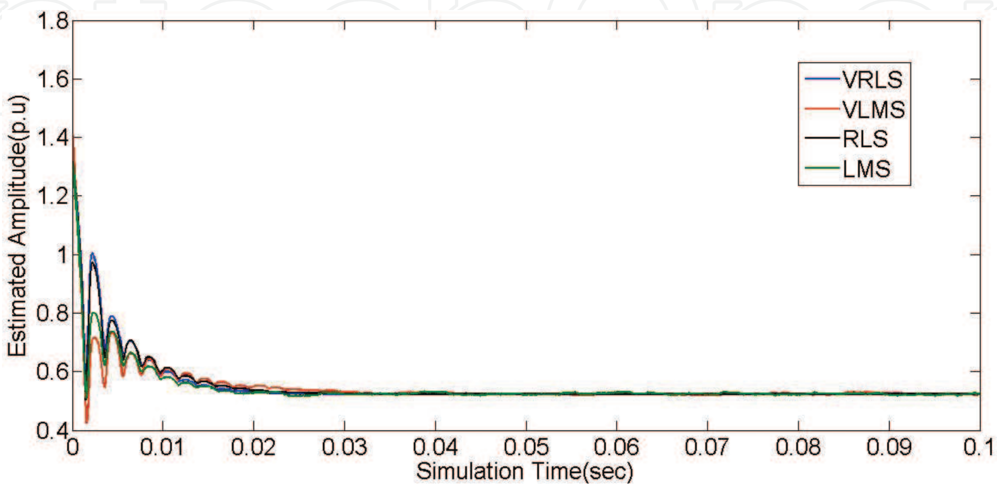


**Figure 12.** Comparison results of fundamental phase.

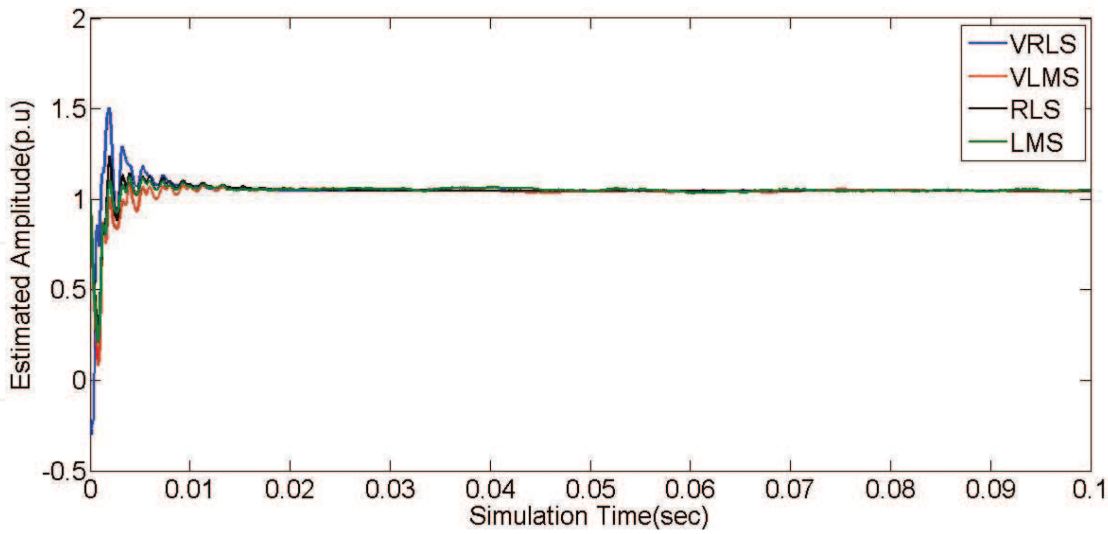


**Figure 13.** Comparison results of third harmonic phase.

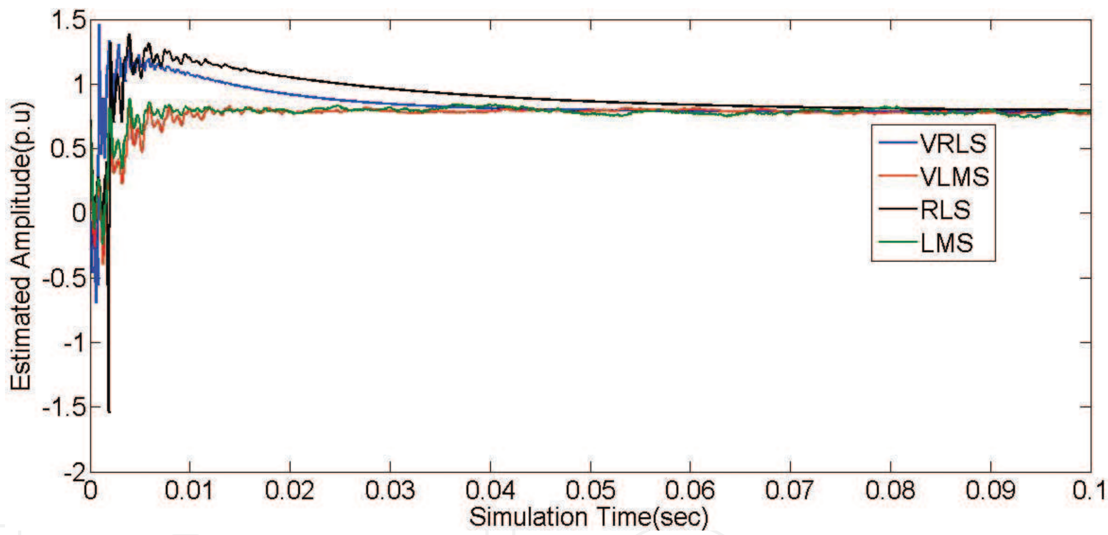


**Figure 14.** Comparison results of fifth harmonic phase.

### 8.3. Case-3

By using PQD signals from IEEE-1159-PQE databases distorted signal is generated for testing of VRLS algorithms and reconstructed signals are compared with the original signals. It is observed that VRLS tracks the distorted signal accurately as given in **Figure 15**.

### 8.4. Case-4

To validate the performance of VLMS/F algorithm, harmonic signal is generated in MATLAB/SIMULINK environment considering three phase rectifier as a load as shown in **Figure 16**.

http://dx.doi.org/10.5772/intechopen.74581

Signal generated in each phase is compared with the estimated signal from the proposed algorithm. It is observed from **Figures 17–19** that VLMS/F tracks the distorted signal accurately.

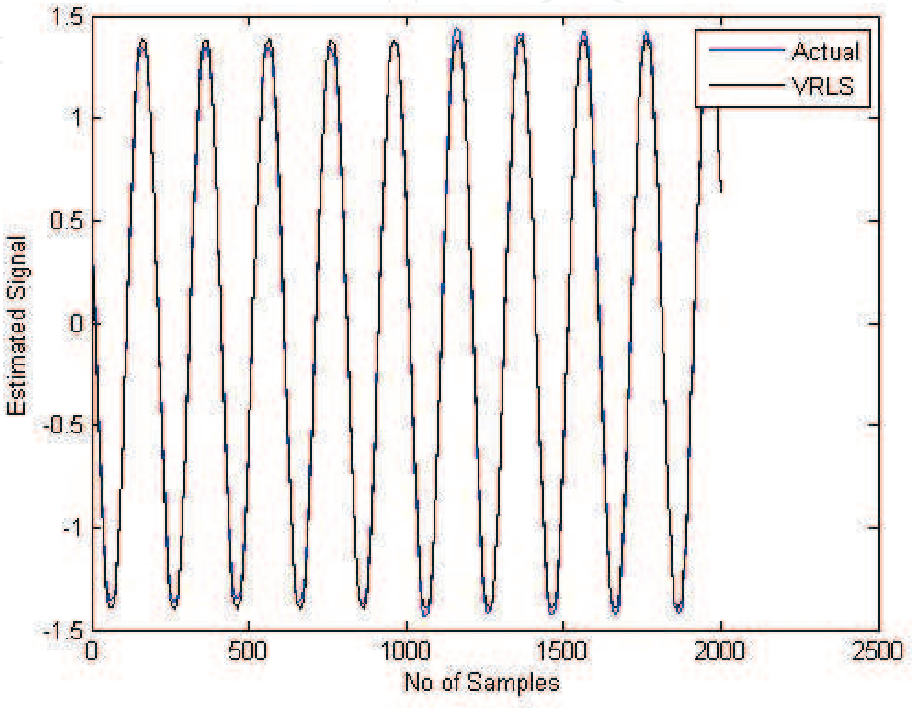


**Figure 15.** Estimated signal.

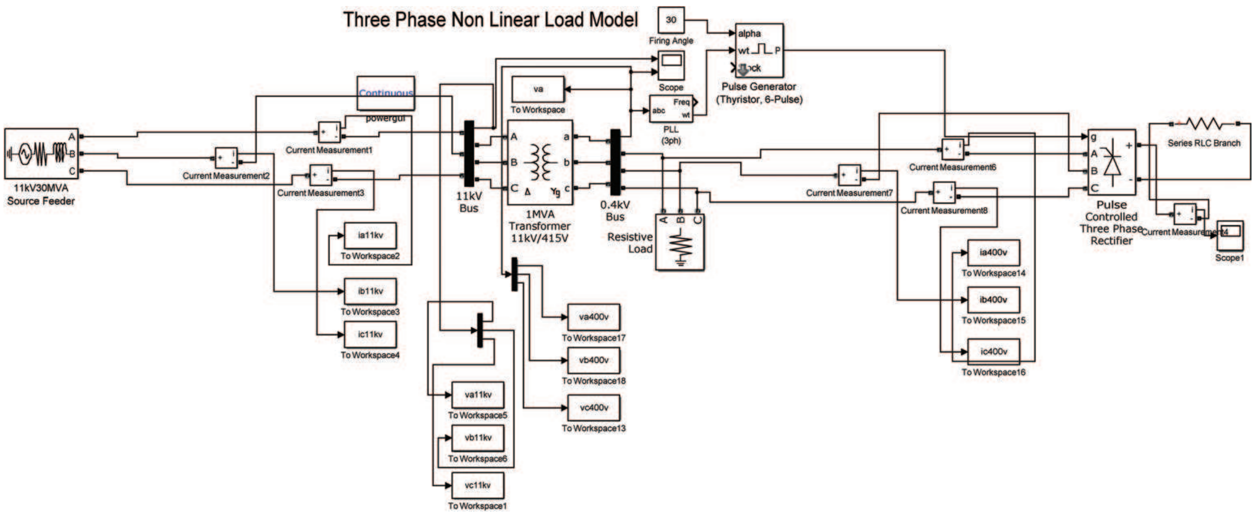


**Figure 16.** Three phase nonlinear load model.

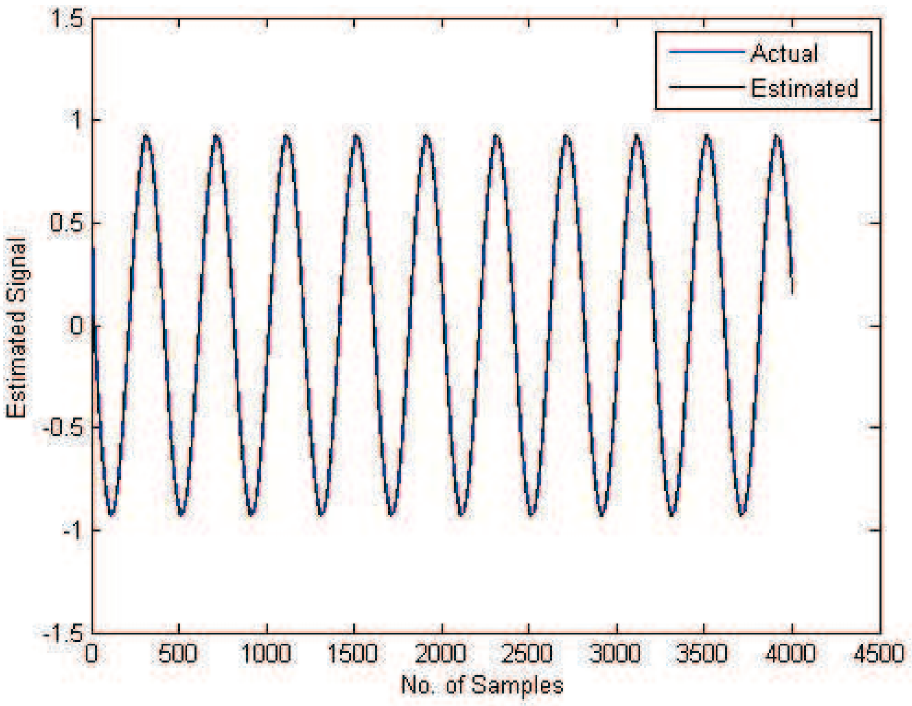


**Figure 17.** Estimated signal in phase a.

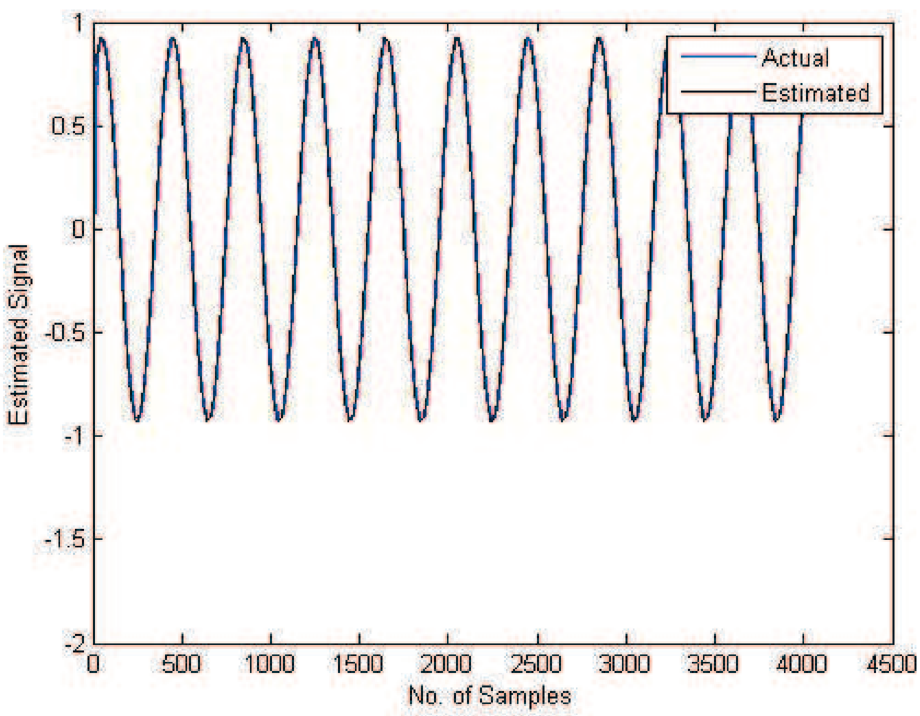


**Figure 18.** Estimated signal in phase b.

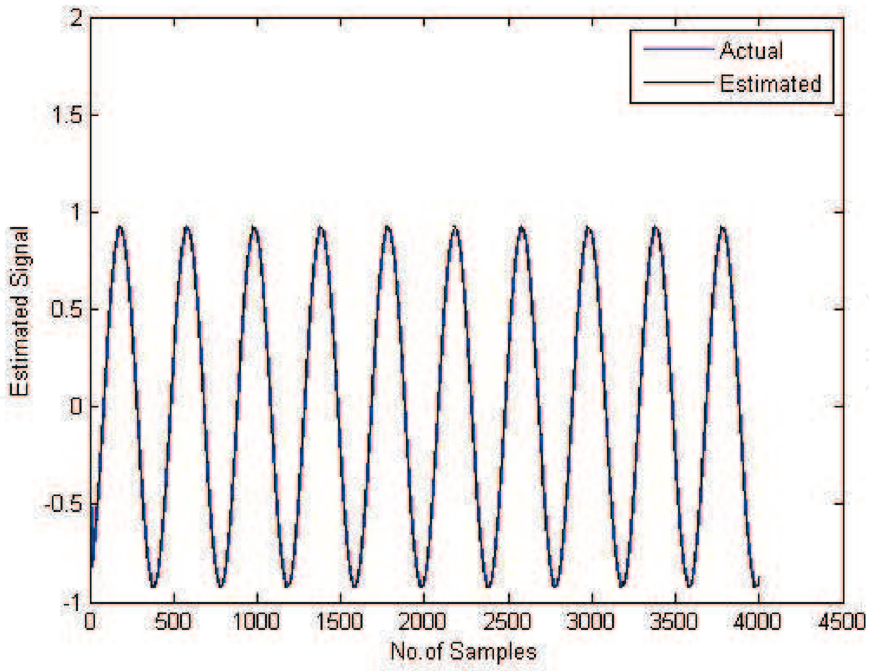


**Figure 19.** Estimated signal in phase c.

## 9. Conclusion

The chapter analyses different adaptive filtering models used to estimate harmonic amplitudes and phases in distorted power signals. Performances of Volterra series based adaptive filters are established through comparison results obtained through MATLAB simulations. It is quite apparent that VLMS/F filter gives better harmonic estimation accuracy as compared to LMS, VLMS and LMS/F. With a proper compromise between LMS and LMF, VLMS/F provides stable convergence of estimation error. Similarly Volterra RLS based harmonic estimation model provides faster and stable convergence with minimum estimation error.

## Author details

Harish Kumar Sahoo[1]* and Umamani Subudhi[2]

*Address all correspondence to: harish_sahoo@yahoo.co.in

1 Department of Electronics and Tele Communication Engineering VSSUT, Burla, India

2 Department of Electrical and Electronics, IIIT Bhubaneswar, India

## References


[1] Smith JC, Hensley G, Ray L. IEEE recommended practice for monitoring electric power quality. IEEE Studies. 1995:1159-1995

[2] Reid WE. Power quality issues-standards and guidelines. IEEE Transactions on Industry Applications. 1996;**32**(3):625-632. DOI: 10.1109/28.502175

[3] Electrical Power Systems Quality. 3rd ed. India: McGraw-Hill Education; 2012. p. 558. DOI: 9780071761550

[4] Bollen MH, Gu I. Signal Processing of Power Quality Disturbances. 30th ed. New York: John Wiley-IEEE; 2006

[5] Haykin SS. Adaptive Filter Theory. Englewood Cliffs, N.J: Prentice-Hall; 1986

[6] Begovic MM, Djuric PM, Dunlap S, Phadke AG. Frequency tracking in power networks in the presence of harmonics. IEEE Transactions on Power Delivery. 1993;**8**(2):480-486. DOI: 0885-8977/93

[7] Carugati I, Orallo CM, Donato PG, Maestri S, Strack JL, Carrica D. Three-phase harmonic and sequence components measurement method based on mSDFT and variable sampling period technique. IEEE Transactions on Instrumentation and Measurement. 2016;**65**(8): 1761-1772. DOI: 10.1109/TIM.2016.2552679

[8] Pradhan AK, Routray A, Basak A. Power system frequency estimation using least mean square technique. IEEE Transactions on Power Delivery. 2005;**20**(3):1812-1816. DOI: 10.1109/TPWRD.2004.843453

[9] Joorabian M, Mortazavi SS, Khayyami AA. Harmonic estimation in a power system using a novel hybrid least squares-Adaline algorithm. Electric Power Systems Research. 2009;**79** (1). DOI: 10.1016/j.epsr.2008.05.021

[10] Chudamani R, Vasudevan K, Ramalingam CS. Non-linear least-squares-based harmonic estimation algorithm for a shunt active power filter. IET Power Electronics. 2009;**2**(2):134-146. DOI: 10.1049/iet-pel:20080006

[11] Kennedy K, Lightbody G, Yacamini R. IEEE. In: Power System Harmonic Analysis Using the Kalman Filter. 2nd ed. 2003. pp. 752-757. DOI: 10.1109/PES.2003.1270401

[12] Clarkson PM, Dokic MV. Stability and convergence behaviour of second-order LMS Volterra filter. Electronics Letters. 1991;**27**(5):441-443. DOI: 10.1109/e1:19910279

[13] Singh TSD, Chatterjee A. A comparative study of adaptation algorithms for nonlinear system identification based on second order Volterra and bilinear polynomial filters. Measurement. 2011;**44**(10):1915-1923. DOI: 10.1016/j.measurement.2011.08.028

[14] Gui G, Peng W, Adachi F. Adaptive system identification using robust LMS/F algorithm. International Journal of Communication Systems,Wiley Online Library. 2014;**27**(11):2956-2963. DOI: 10.1002/dac.2517

[15] Walach E, Widrow B. The least mean fourth (LMF) adaptive algorithm and its family. IEEE transactions on Information Theory. 1984;**30**(2):275-283. DOI: 10.1109/TIT.1984.1056886

[16] Lim SJ, Haris JG. Combined LMS/F algorithm. Electronics Letters. 1997;**33**(6):467-468

[17] Subudhi, Umamani and Sahoo, Harish Kumar. Harmonics and decaying DC estimation using Volterra LMS/F algorithm. In: Power Electronics, Intelligent Control and Energy Systems (ICPEICES), IEEE International Conference on; 4–6 July 2016; DTU. Delhi,India: IEEE; 2016. p. 1-5. DOI: 10.1109/ICPEICES.2016.7853663

IntechOpen

IntechOpen

IntechOpen

IntechOpen