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Application of three intelligent methods for harmonic estimation: Adaline, Adaline-LS, PSO-LS

H. Erdem [1], E.O. Tartan [2], A. Berkol [1]

1. Institute of Science and Engineering, Baskent University, Ankara, Turkey
herdem@baskent.edu.tr, ali.berkol@yahoo.com

2. Vocational School of Technical Sciences, Baskent University, Ankara, Turkey,
onertartan@baskent.edu.tr

***Abstract* – Harmonic estimation is one of the main challenges in electric power quality discussion. During the last decade many deterministic and machine learning based methods have been applied for estimation of harmonics' parameters. Concerning learning capacity of intelligent systems, adaptive linear combiner (Adaline) based method is the most used learning method among the artificial neural networks (ANN). On the other hand, some meta-heuristic optimization algorithms and the related hybrid algorithms have been applied for harmonic estimation in recent studies. This study discuses and compares, application of three Artificial Intelligent (AI) methods (Adaline, Adaline-Least squares (LS) and Particle Swarm Optimization-LS) for harmonic parameters estimation in power signals. The proposed algorithms have been applied to a sample test signal and the performances of methods have been compared considering estimation accuracy and estimation time.**

Keywords- Harmonic, Power Signal, Adaline, PSO, Least Square

I. INTRODUCTION

In electric power quality discussion a main challenge is the estimation of harmonics. In these systems voltage and current harmonics result in efficiency reduction in delivered energy. The harmonic definition is deviation of the power signal from its ideal sinusoidal waveform [1]. This non-sinusoidal waveform contains a set of sinusoidal waveforms with different amplitudes and phases and frequencies. The signal with integer multiples of fundamental frequency are called as integer harmonics. The other harmonic components with non-integer harmonics are evaluated as interharmonic or sub harmonics if their frequency is lower than fundamental frequency.

Although the generated electric power is transferred as a sinusoidal voltage waveform to loads and users, increasing use of nonlinear loads containing power electronic switching element (UPS, Motor drivers, Transformers, Arc furnace, Low power lighting system) causes to generate a non-sinusoidal current. As an example system, Figure 1 presents, the relation between AC voltage source and nonlinear load. Increasing the power quality is directly related to correctly estimation of the harmonic components [1].

Many methods have been proposed to estimate the components of power system harmonics [2]. Among the used methods, time domain methods present better performance than frequency domain based harmonic analysis algorithm. From frequency domain based methods, Fast Discrete Fourier (FFT) is the widely used and well known harmonic analysis method [3]. Although FFT is used commonly, this method suffers from inaccurate results due to leakage and the picket fence effects [4, 5]. In order to improve the estimation accuracy, in recent years, AI methods have been applied to estimate the harmonic component.

From the AI methods, learning based algorithm or optimization based heuristic algorithms are the most used algorithms for harmonic estimation. These methods can be classified in three classes (Figure 2). In the first class, Multi-layer perceptron and Radial Basis Function ANN need sufficient number of sample patterns for learning and these methods require training time. The second group contains Adaline-based approaches. Adaline as a well-known single neuron ANN structure has been used in adaptive signal processing in many applications. Although this method has been preferred in many harmonic estimation applications [6, 7, 8, 9, 10], the performance of this method depends on initial weight values. In order to improve accuracy and estimation time, Adaline-based hybrid estimation algorithms have been suggested in other studies [11, 12].

Figure 1. AC source and current signal with harmonics

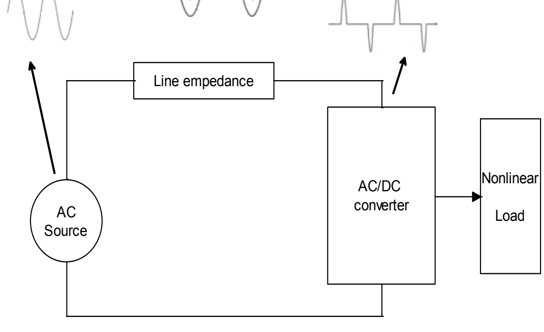
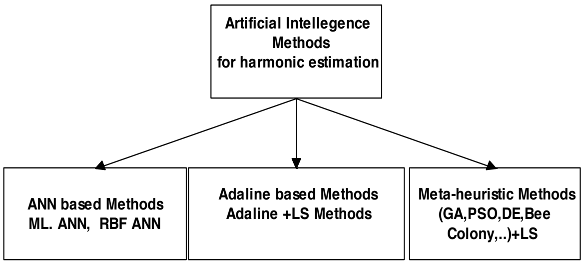


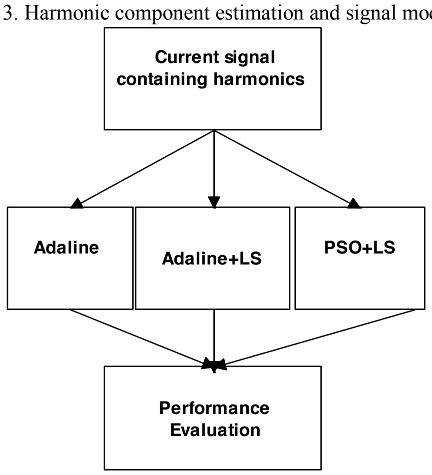
Figure 2. Classification of using AI methods for harmonic estimation



Third class methods, meta-heuristic optimization algorithms as intelligent search method have been applied in recent studies for harmonic estimation [13, 14, 15, 16]. In these methods, a system structure matrix model has been used for estimation of harmonics. In hybrid methods generally LS method has been used to calculate the corresponding amplitudes and meta-heuristic method has been applied to estimate other parameters.

This study compares performance of the most used intelligent harmonic estimators. Adaline, Adaline+LS, and PSO+LS methods have been compared for harmonic estimation considering accuracy and calculation process time. Figure 3, presents the proposed methods. Section two presents the proposed methods and signal modeling approach. Section three presents the simulations and results.

Figure 3. Harmonic component estimation and signal modelling



II. THE PROPOSED MODELLING APPROACHES

In the proposed study, three methods have been compared for integral harmonic estimation. As given in Figure 3, these methods are as follows.

- Adaline,
- Adaline+least mean squares,
- PSO+ least mean squares,

Estimation of harmonic components of the signal is the first step in designing filter to reduce the effects of unwanted waveforms in order to increase the power quality. As presented in literature review, in recent studies, AI has drawn much attention for the estimation of harmonics. From the applied methods, Adaline and Adaline+LS are the most used ANN structures for harmonic estimation. On the other hand, using meta-heuristic search methods in combination with the LS algorithm has also attracted researchers' attention for harmonic estimation challenge. As presented in LS-based hybrid studies, LS as a linear estimator has been used to estimate amplitudes of harmonics and Adaline structure has been used to calculate phases. Similarly, meta-heuristic search methods (GA, PSO, and etc.) can be used to estimate harmonics' phases.

Combining, these search methods with LS can be used to estimate harmonics' phases and amplitudes. This approach assumes the harmonic estimation problem as linear and nonlinear models. Amplitude estimation process can be evaluated as linear model and phase estimation stage can be defined as nonlinear model. All applied methods need a signal model including noise. Therefore, the estimated signal and related definition and all assumed estimated parameters have been given in Table1. Additionally, two hybrid models (Adaline+LS, PSO+LS) need a structure matrix which is given in Equation (7). Each column of this matrix multiplied by its amplitude gives a harmonic component. For estimating interharmonics and fundamental frequency deviation, additional columns can be included in system matrix in PSO-LS method.

Table 1. Power signal: its components and the estimation model

A periodic signal	$Z(t)=\sum_{n=1}^{N} A_n \sin(\omega_n t + f_n)$ (1)
Discrete time signal	$Z(kTs)=\sum_{n=1}^{N} A_n \sin(\omega_n kTs + \phi_n)$ (2)
N	Number of harmonics, n =1,2,…, N
K	Sample number k=1,2,…., K
T_s	Sampling rate
A_n	Amplitude of each harmonic
$Ø_n$	Phase of harmonic harmonic
f_o	Fundamental frequency
$\omega_n : 2\pi n f_0$	Angular frequency of nth harmonic
v	Noise
Estimated signal	$\hat{Z}(t)=\sum_{n=1}^{N} \hat{A}_n \sin(\omega_n t + \hat{\phi}_n)$ (3)
Actual amplitudes	$A = [A_1 \quad A_2 \quad \dots \quad A_n]^T$ (4)
Actual model	$Z = H.A + v$ (5)
Estimated model	$\hat{Z} = \hat{H}\hat{A}$ (6)
H	System structure matrix
$\hat{H}$	Estimated system structure matrix
Estimated amplitudes	$\hat{A} = (\hat{H}^T.\hat{H})^{-1} \hat{H}^T Z$ (7)

In population based optimization algorithm, to terminate optimizing or learning process and search steps, an object function must be defined. In signal processing approach. The difference between sampled actual signal and the reconstructed one, which is the estimated of actual signal, can be defined as fitness or object function which is given in Equation (8). In Adaline-based approch, this error equation can be used for weight tuning. Similarly, in optimization based method, this function must be minimized.

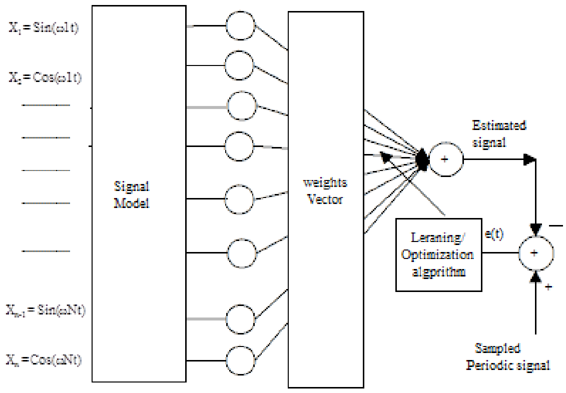
$$H = \begin{bmatrix} \sin(\omega_1 t_1 + \phi_1) & \cdots & \sin(\omega_N t_1 + \phi_N) \\ \sin(\omega_1 t_2 + \phi_1) & \cdots & \sin(\omega_N t_2 + \phi_N) \\ \vdots & & \vdots \\ \sin(\omega_1 t_k + \phi_1) & \cdots & \sin(\omega_N t_k + \phi_N) \\ \vdots & & \vdots \\ \sin(\omega_1 t_K + \phi_1) & \cdots & \sin(\omega_N t_K + \phi_N) \end{bmatrix} \quad (8)$$

$$f = \sum_{k=1}^{K} \left[Z(k) - \hat{Z}(k) \right]^2 \quad (9)$$

A. Adaline for Harmonic Estimation

Adaline is a single neuron ANN structure which widely used for linear classification and adaptive signal processing applications. In Adaline structure, LMS learning algorithm as an error based learning algorithm has been used for tuning of weights. Figure 4 shows general structure of the Adaline. As given in the figure, in learning process, the summed and the weighted signal has been compared with the target periodic signal for tuning the weights of the ANN. The learning process is an optimization approach for minimizing error function.

Figure 4. Adaline model for harmonic estimation.



B. PSO for Harmonic Estimation

PSO as a meta- heuristic population based optimization algorithm is used to solve complex optimization problems. To formulate the problem, each solution candidate searching minimum/maximum objective function is called as particle in analogy to a bird or a fish in a swarm and for each particle a randomized velocity is assigned. The optimization algorithm relies on the information exchange between particles (fishes or birds) in food search action. In the optimization steps, each particle adjusts its own trajectory (p_{best}; p_{id}), and modifies its trajectory considering position of other particles in swarm (g_{best}; p_{gd}) [17-19]. The position of each particle has been updated to find the best global solution [17]. The steps of optimization and the related formulation have been given in Table 2.

To improve the optimization algorithm's performance, new coefficient (weighting coefficient 'w') can be defined to control the particle's exploratory behavior. Equation (13) presents relation of "w_{max}", "w_{min}" and iteration numbers.

Moreover, to increase search process, inertial weight can be decreased during iteration linearly from 0.9 (w_{max}) to 0.4 (w_{min}) [18]. In applied PSO version called Particle Swarm Optimization with Passive Congregation (PSOPC), acceleration constants c_1, c_2 and c_3 are accepted as suggested in [14].

Table 2. Algorithm of PSO and the related formulation.

PSO algorithm steps:
Initialize rand. velocity and position between [0,π]
Do
For i = 1 to swarm size (asummed solutions)
Calculate fitness function (fit)
If fit < best pattern
ith particle best position=ith particle position
best pattern=fit
end if
end for
find min best pattern and corresponding particle
For i = 1 to swarm size
Update velocity v_{id}
Update position x_{id} in [0,π]
end for
while break if maximum/ minimum iterations error holds

$$v_{id} = v_{id} + \varphi_1(p_{id} - x_{id}) + \varphi_2(p_{gd} - x_{id}) + \varphi_3(p_{rd} - x_{id}) \quad (10)$$

$$\varphi_i = c_i \text{rand}() \quad (11)$$

$$x_{id} = x_{id} + v_{id} \quad (12)$$

$$\omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{iter_{max}} iter \quad (13)$$

III. APPLICATION OF THE PROPOSED ALGORITHMS

To compare the performances of the suggested methods, simulations using sampled real data have been performed in MATLAB environment on a PC with a 2.93-GHz Intel Core 2 Duo CPU and 2.00-GB RAM. The applied current signal has been selected from similar studies [13]. The test signal and sample system that the signal is obtained is shown in Figure 5. The current signal from nonlinear load has been recorded. This signal contains odd harmonics. These harmonics order are as 5, 7, 11, 13th harmonics given in Table 3. Table shows phase and amplitude of each component. Due to the random initialization in Adaline and PSO-based estimation models, simulations are repeated for 1000 times and average error values have been considered.

Figure 5. Sample system: A three-phase AC/DC power converter

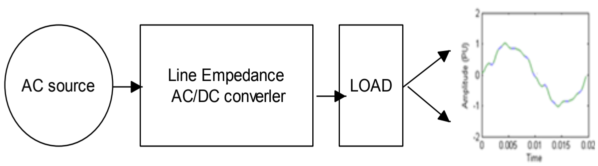


Table 3. Harmonic content of the test signal [13]

Harmonic Order	Amplitude (p.u.)	Phase (Degrees)
Fundamental (50 Hz)	0.95	-2.02
5th (250 Hz)	0.09	82.1
7th (350 Hz)	0.043	7.9
11th (550 Hz)	0.03	-147.1
13th (650 Hz)	0.033	162.6

Firstly, Adaline and Adaline-LS methods have been compared. In Adaline+LS method, after estimating phase angles with Adaline, involving LS for amplitude estimation can improve estimation performance. Although calculation of system matrix in Adaline-LS model results in a longer process time in one iteration, it may reach same error at lower iteration number than Adaline. Considering the estimated amplitudes at first iteration, accuracy results of the two methods in comparison with actual amplitudes are visualized in Figure 6. As seen from figure, the accuracy of the estimated amplitude for Adaline+LS is better than standalone Adaline approach. To track the performance of the methods along next iterations, reconstructed signals in the first four iterations are shown in Figure 7.

Convergence of error in Adaline and Adaline-LS in a logarithmic scale is depicted in Figure 8. Additionally, a more detailed process time and final convergence error results have been given in Table 4. As Figure 7 and Table 4 shows, at even its first iteration Adaline-LS can give more accurate estimation than standalone Adaline at its second iteration. Considering total squared error and run time, it is seen that with lower iteration number Adaline-LS may yield lower process time than standalone Adaline.

Secondly, hybrid algorithm composed of PSO and LS algorithm has been applied for the same input power signal. Similar to Adaline+LS algorithm, this method needs structure matrix for amplitude calculation with LS. In this method, phase optimization is provided PSO and and corresponding amplitudes are calculated by LS iteratively. In simulations maximum number of generations for PSO is chosen as 80, since it ensures convergence. Figure 9 presents change of objective function versus generation. It can be seen from the change of objective function that objective function reaches minimum value in nearly 60 generation.

To provide comparison the run time of the methods, total time of the convergence has been given in Table 5. Evaluating of the applied methods regarding to tables and figures shows that the final error is higher in PSO+LS in comparison with the Adaline-based methods. Moreover calculation or convergence time is longer for PSO-based system due to calculation of structure matrix and population based structure.

The performance of the Adaline-based approach is in acceptable range for practical applications. On the other hand in PSO-based system, estimation of interharmonic and fundamental frequency deviation can be provided by inserting additional column to structure matrix, but estimating the. Similar component in Adaline-based method needs additional calculations.

Figure 6. Amplitude estimation accuracy at first iteration with Adaline and Adaline-LS

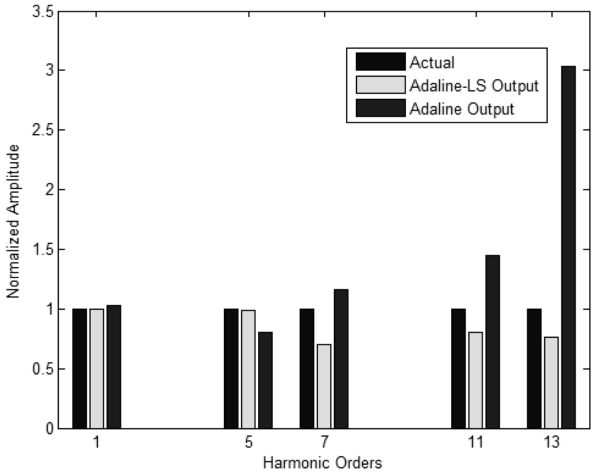


Figure 7. The estimated signal by Adaline and Adaline-LS in 4 iteration

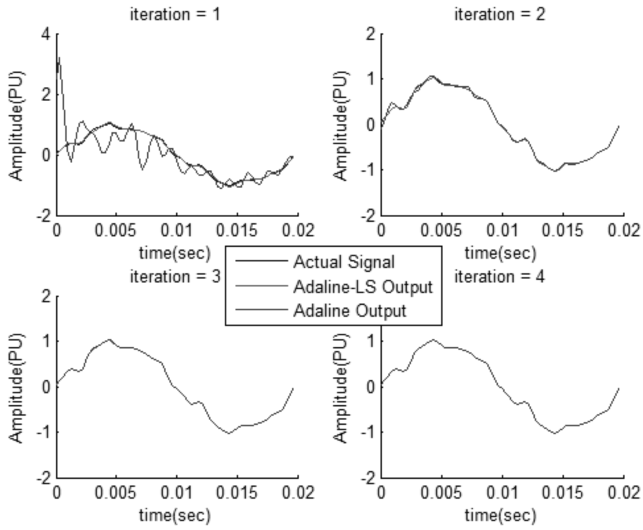


Figure 8. Total square error for Adaline, Adaline-LS in logarithmic scale

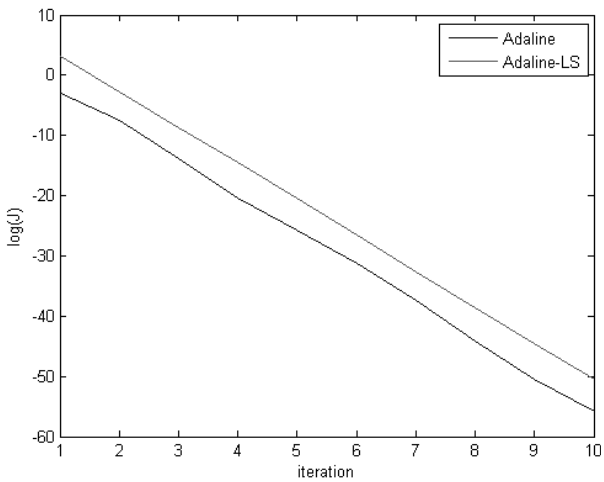


Figure 9. Total Squared Error for PSO+LS algorithm

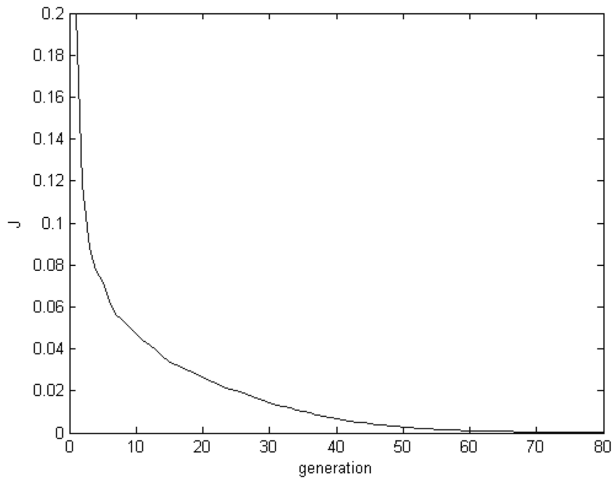


Table 4. Error and process time in Adaline-LS and Adaline

Iteration	Adaline		Adaline-LS	
	Total Squared Error	Time (ms)	Total Squared Error	Time (ms)
1	24.3192	0.38	0,0469	0.44
2	0.0573	0.76	5.4710e-004	0.88
3	1.7497e-004	1.15	8.9690e-007	1.32
4	5.1825e-007	1.51	1.2557e-009	1.75
5	1.2931e-009	1.89	4.2271e-012	2.20
6	2.7427e-012	2.31	2.3177e-014	2.64
7	6.0345e-015	2.68	5.4005e-017	3.11
8	1.6463e-017	3.03	7.3028e-020	3.49
9	4.6918e-020	3.44	1.1409e-022	3.95
10	1.1427e-022	3.81	5.4867e-025	4.37
11	2.4025e-025	4.15	2.2211e-027	4.83
12	5.3862e-028	4.56	1.0176e-029	5.30
13	4.2271e-030	4.95	4.6011e-030	5.62

Table 5. Error and process time Adaline-LS, Adaline and PSO-LS

	Adaline (*I*=13)	Adaline-LS (*I*=13)	PSO-LS (*G*=80)
Error	4.2271e-030	4.2271e-030	3.0534e-004
Time	4.95 ms	5.62 ms	394,15ms

It may be possible combining the advantages of least squares, Adaline and meta-heuristic methods in a single algorithm in order to reduce calculation time, the estimation error, initialization problem and to estimate frequency deviation. Moreover, in the comparison of the applied method practical implementation possibility must be considered.

IV. CONCLUSIONS

Comparison of three AI based harmonic estimation algorithms have been compared in the proposed study. Three methods have been applied on a current signal recorded from a real system, and the estimation results have been compared regarding to the estimation error and run time. Comparison results show that Adaline-based method, especially Adaline +LS methods gives acceptable performance than PSO-based method. On the other hand, PSO-based approach supports calculation of other harmonic parameters (interharmonic, fundamental frequency) by expanding system structure matrix. Calculating of the same parameters in Adaline-based methods needs additional computation. From the practical implementation point view, Adaline-based methods can be implemented on FPGA circuit considering parallel processing capacity of these circuits. Combination of two hybrid methods may provide improvement in accuracy and estimation time.

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