

A Hybrid Water Cycle Algorithm-Least Square based Framework for Robust Estimation of Harmonics

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ABSTRACT

The power quality is becoming an extensively addressing aspect of power system because of sensitive operation of smart grid, awareness of power quality and modern power system equipment. This paper proposes a new hybrid framework of Water Cycle Algorithm-Least Square (WCA-LS) for estimation of harmonics present in time varying noisy power signals. Water Cycle Algorithm (WCA) is a population based algorithm which realizes the concepts of exploitation and exploration to find global optimal in search space under consideration. This algorithm exploits the concept of natural hydrologic cycle to perform heuristic optimization. In hydrologic cycle water flow in the form of streams, rivers and sea. When the rain falls from clouds and snow melts from glaciers, water flows downhill in the form of streams. When streams combine at one point they generate rivers which ultimately fall into the sea. Water from lakes is evaporated and the trees also transpire the water during photosynthesis process into atmosphere to generate clouds. These clouds release water back to the earth in the form of rains and precipitation to complete the cycle. The Proposed approach has been applied on test system from literature and results prove the effectiveness of technique in terms of precision and computational time. Results are further authenticated by estimating harmonics of real time voltage waveform of Axial Flux Permanent Magnet Synchronous Generator (AFPMSG). The proposed WCA-LS delivers promising results compared to some of the state of art frameworks such as Genetic Algorithm (GA) and Particle Swarm Optimization with Passive Congregation based Least Square (PSOPC-LS).

1. Introduction

With rapid increase in power demands maintaining the quality of delivered power is a very challenging task for reliable operation of both conventional power system and smart grid [1]. Smart grid is a power system which utilizes advance communication and monitoring technology to improve the grid performance. It has capacity to self heal from power transients, incorporating efficient energy management, automation and smart metering. However, due to extensive use of power electronics based nonlinear devices, sensitive loads, presence of advance metering, sensing and control mechanisms the performance of smart grid not only downgrades significantly but the quality of power delivered in power system also deteriorates [2-4]. The distortions in fundamental waveforms due to switching of solid state devices may be termed as harmonics. These harmonics pose huge amount of problems to power system thus negatively effecting the reliability of system. Harmonics accelerate the process of skin effect, eddy's currents and corona loss. Failure of devices like capacitors, circuit breakers and overheating of transformers and rotor of motors is more likely in environment having harmonics. Reduced selectivity of relays and poor consistency of protection schemes is another concern related to harmonic pollution. Electromagnetic interference is another fatal effect of harmonics [5, 6]. Keeping in view of all these negative aspects it is therefore important to develop fast, less complex and more efficient methods to evaluate power quality by detecting and mitigating these harmonics in power waveforms [1]. By evaluating harmonics we can

design efficient compensators and filters to counteract against aforementioned problems related to harmonics caused by different types of devices [7, 8].

The Harmonic estimation is modelled as dynamic multimodal optimization problem. Researchers have so far tackled this complex estimation problem using different mathematical, statistical and heuristic approaches. Evaluation of harmonics incorporates estimation of both amplitudes and phases of harmonics. Actual model of harmonics includes linear estimation of amplitudes and nonlinear estimation of phases [6, 9, 10].

Mathematical techniques like Fourier transform (FT) and derivatives of FT like DFT (Discrete Fourier Transform) and FFT (Fast Fourier Transform) have a vast history of estimating multiple frequency terms out of distorted sinusoidal signals. FT based approaches are only suitable for stationary signal [11-13]. As our power system is becoming more and more complex due to tremendous inclusion of nonlinear loads, effectiveness of DFT and FFT is diminishing due to time varying harmonics, aliasing, leakage and famous picket and fence phenomena [14, 15]. Similarly, Hilbert and wavelet transforms (WT) also have found various applications in harmonic estimation. WT based techniques are multi resolution methods in which source signal is alienated in further sub frequencies. As original signal is randomly selected, estimation varies and results are therefore partially accurate [6]. Artificial intelligence based approaches like neural networks (NN), Fuzzy logic (FL) and Adaline are also incorporated to

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successfully approximate the harmonics out of distorted power signals [6, 16].

A wide spectrum of statistical approaches such as Kalman Filter (KF), Linear Least square (LLS), Least Mean Square (LMS), recursive least square (RLS), least absolute value (LAV) and corresponding modification of these techniques have been employed in estimation of harmonics from distorted signals. Statistical approaches have rather tackled this nonlinear problem efficiently. KF and their derivatives are linear, robust and efficient statistical tools and their utilization in estimation of harmonics is quite effective [17, 18]. But they require prior knowledge about system and fundamental frequency. Furthermore they also require fine tuning to extract appropriate estimations and Kalman state matrix also needs initialization [17]. Singh et al. [1] have discussed local ensemble transform based KF (LET-KF) to deal with crafty estimation of harmonics, inter harmonics and sub harmonics. Moreover, proposed approach has the capability to deal with both stationary and dynamic distorted signals. This approach deals with the state matrix by reducing the search space of matrix and overall there are lesser multiplicative operations so LET-KF takes lesser computational time compared to KF and Ensemble-KF (En-KF) [19]. Accuracy of proposed modified KF is rather apparent since distorted power waveform belongs to large paper industry. Aside KF, other statistical approaches being utilized are LS and LMS [2, 20]. Kwong and Johnston [21] exploited an adaptive variable step least mean square (LMS) successfully to estimate the harmonics in noisy waveforms. According to these authors, this approach produced small steady state error during estimation. Step size has been adaptable in this sense that with small step size there is small miss adjustment and with large step size there is rapid tracking. Step size is adjusted through square of prediction error where large prediction error gives large step size and similarly small prediction error gives small step size. Results are improved compared to static step LMS. Similarly, Al-Feilat et al. [7] has discussed comparison of different mathematical and statistical tools in estimation of harmonics in power system. They have compared the performance of DFT, Least square (LS) and least absolute value (LAV) with factors like SNR, number of samples, sampling frequency, computational time and missing data. Real time data from 6 pulse converter is employed to evaluate the performance of these techniques. It's quite clear from these results that for noise free environment each discussed technique works effectively identical but in case of noisy environments LAV overall performs better for missing data when compared to other methodologies. However, due to statistical background LAV requires prior information for fundamental frequency and is sensitive to variations in fundamental frequency [22]. Bettayeb and Qidwai [8] have accomplished online estimation of harmonics using recursive least square (RLS). Using RLS, both amplitudes and phases are effectively evaluated.

Distorted waveform from six pulse rectifier has been tested to gauge performance of this method. Furthermore, problem model has incorporated various SNR values. Results are successively updated as soon as samples are received. Even for 0 dB SNR fair approximation of both amplitude and phase of harmonics has been performed using mentioned approach. Proposed method shows enhanced results compared to LS and weighted least square (WLS). Statistical approaches are also hybridized with mathematical approaches to falter with estimation problem proficiently. Singh et al. [23] have discussed the maiden application of novel variable constraint least mean square (VCLMS) to estimate the power system harmonics. Both phases and amplitudes of integer, inter and sub harmonics are effectively estimated out of distorted power signals through this technique in noisy environments. The problem has been modelled with both stationary and dynamic signals where data from solar connected inverter has been utilized to show the effectiveness of approach. The technique has been compared with similar statistical approaches from literature e.g. LMS, Normalized LMS and variable leaky LMS. Results show the effectiveness of proposed methodology against similar algorithms. Lobos et al. [2] have discussed the estimation of harmonics in power using linear least square (LLS) and SVD; where decomposition is used to compute the LLS solution and fundamental frequency has been predicted through heavily distorted signal. Results are competitive albeit with higher complexity. Ashraf et al. [24] proposed new heuristic hybrid algorithm called, 'advanced gravitational search based least square estimator (AGSA-LS)' for efficient estimation of different types of harmonics from non-noisy as well as noisy signals.

Time varying harmonics and non-stationary signals have paved the path of researchers to apply intelligent and self-adaptable nature inspired heuristic algorithms to estimate harmonics in slanted waveforms. Moreover, heuristic algorithms are often hybridized with statistical approaches to obtain accurate estimates of harmonics. Bettayeb and Qidwai [9] have incorporated linear least square (LLS) with Fuzzy Bacterial foraging (BF) to estimate both amplitudes and phases of harmonics from distorted signal with additive noise and decaying DC offset. Real model of distorted waveform usually has linear amplitudes and nonlinear phases. The amplitude is estimated through LLS whereas phase has been estimated through adaptive BF algorithm. Nonlinear estimation of phase is rather a complex problem so run step length in BFA has been modified with adaptive Takagi-Sugeno fuzzy scheme to make convergence faster. Results are validated by comparing proposed methodology against DFT and Genetic Algorithm (GA). Proposed algorithm falter well with complexities in much better way in lesser amount of time taken when compared with GA and DFT. Mishra [10] has utilized hybrid least square (LS) GA based algorithm for harmonic estimation. LS has been utilized for estimation

of amplitude and GA has been modified to estimate the phase of harmonics. The iterations alternate between GA and LLS for successful approximation of estimates. Proposed topology shows better results against similar techniques from literature. Lu et al. [25] have established optimal power system harmonics estimator using particle swarm (PS) optimizer. Here PSO with passive congregation (PSOPC) has been hybridized with LS to efficiently guess both nonlinear phases and linear amplitudes of harmonics. Both techniques are alternatively executed to reduce the error between original and reconstructed signal. This methodology has been compared with both DFT and GA and the results prove worthiness of proposed topology. Subudhi and Ray [5] have discussed hybrid Adaline and BFA to correctly estimate the phases and amplitudes of integer, inter and sub harmonics. Here BF strategy is made adaptive by updating weights of Adaline by taking initial weights as outputs of BFO. Ji et al. [26] have incorporated hybrid adaptive bacterial foraging optimizing to estimate the linear amplitudes as well as nonlinear phases of integer, inter and sub harmonics. BFO due to its inherent capability of dealing with multimodal problems has been exploited to deal with estimation of nonlinear phases of harmonics, whereas amplitudes have been estimated using LLS. Proposed approach shows better results when compared with GA, a similar heuristic algorithm. Singh et al. [27] have carried parameter estimation of harmonics in power signal using fast transverse Recursive least square (FTRLs) algorithm. The technique has been altered to correctly estimate the amplitude, phases and frequency of power signal in environment having white Gaussian noise. The accuracy of technique is justified by comparison with both forgetting factor least square (FFRLS) and RLS algorithms and it's evident from results that proposed technique is superior to similar solutions. Singh et al. [28] have discussed hybrid firefly algorithm based least square (FA-LS) method to effectively estimate both amplitude and phases of harmonics in distorted power signals. Phases are usually nonlinear in nature, so they are estimated using more robust firefly algorithm whereas amplitudes are estimated using LS. Real time data from power supply has been utilized to show efficiency of proposed procedure and technique vacillates well against distorted signals when compared with PSOPC-LS [25] and ABC-LS approach [29]. Singh et al. [30] have discussed the hybrid firefly-recursive least square (FF-RLS) algorithm for successful estimation of nonlinear phases and linear amplitudes of integer, inter and sub harmonics. Here firefly has been integrated to develop weights for RLS in successive iterations since RLS require prior knowledge to update the data. Real time distorted signal from solar connected inverter has been drafted to test the usefulness of proposed algorithm. Results are equated to other soft computing techniques like ABC-RLS [29] and BFO-RLS [9]. Proposed approach has the capability to produce much better results in noisy environment. Authors have discussed

the effectiveness of proposed approach in a way that Firefly is itself much better heuristic algorithm compared to other similar algorithms like GA, PSO, ABC and BFO [31, 32]. Frequency Shifting and Filtering (FSF) algorithm has been proposed to estimate the harmonics in variable frequency signals where iterative averaging filter is adopted to eliminate the spectral interferences [33]. Power system harmonic estimation solution based on modified artificial bee colony (MABC) algorithm has been proposed to estimate the amplitudes and phases of different electrical signals [34]. Gravity Search Algorithm (GSA) and Recursive Least Square (RLS) has been investigated to solve the harmonic estimation for time varying electrical signals in presence of different noises [35]. A comprehensive comparison of differential search algorithm (DSA) with other techniques has been presented for efficient, fast and accurate estimation of harmonics [36].

The estimation of harmonics represents a high dimensional search space problem which cannot easily be tackled by traditional computational techniques because search space of the problem increases drastically with its size. Such optimization problem is computationally solved by heuristic algorithms as their ability to reach optimality as well as feasibility is guaranteed. Most of heuristic algorithms have stochastic nature to solve optimization problem starting from initial point, running through successive steps towards optimal points and reaching on global optimum. Water Cycle Algorithm (WCA) has capability to solve highly non-linear, complex and large scale optimization problem like harmonic estimation due to its suitable tradeoff between exploitation and exploration. However, harmonic estimation also requires a proper and suitable modification in WCA to incorporate least square signal attribute. A hybrid method of WCA and LS is therefore proposed to efficiently estimate both amplitudes and phases of harmonics in power signals. The results presented in discussion section prove the performance of proposed WCA-LS method in terms of computational accuracy as well as run time.

2. Problem Formulation for Estimation of Power System Harmonics

Successive approximation of harmonics for power signals constitute two components: linear estimation of amplitudes and nonlinear estimation of phases. Time varying nature of practical signals marks harmonics estimation a very cumbersome problem so it requires proficient and robust algorithm. Mathematically a signal can be modeled as the sum of Sine or Cosine functions with higher order frequencies which are integral multiple of fundamental frequency as given by:

$$S(t) = \sum_{h=1}^H K_h \sin(\omega_h t + \phi_h) + K_{dc} \exp(-\gamma_{dc} t) \quad (1)$$

Where h is the number of harmonic orders, K_h the amplitude of harmonic, ω_h the angular frequency of higher order harmonics, φ_h the phase of harmonic, and $K_{dc} \exp(-\gamma_{dc}t)$ the DC decreasing offset.

$$\omega_h = h \times 2\pi f_1 \quad (2)$$

It might be possible that the signal $S(t)$ is corrupted with some noise N_t , so the complete model of the signal is described as:

$$S(t) = \sum_{h=1}^H K_h \sin(\omega_h t + \varphi_h) + K_{dc} \exp(-\gamma_{dc}t) + N_t \quad (3)$$

The processing of the signal is made easy if it is converted to discrete form, hence the digital version of the above signal is given by:

$$S(mT_s) = \sum_{h=1}^H \left[K_h \sin(\omega_h mT_s + \varphi_h) + K_{dc} \exp(-\gamma_{dc} mT_s) + N_{mT_s} \right] \quad (4)$$

Where T_s is the sampling time. To come up with the estimation of amplitudes and phases of harmonics the trigonometric identity is used, and the signal can be rewritten as:

$$S[m] = \sum_{h=1}^H \left[K_h \sin(\omega_h mT_s) \cos \varphi_h + K_h \cos(\omega_h mT_s) \sin \varphi_h \right] + K_{dc} \exp(-\gamma_{dc} mT_s) + N_m \quad (5)$$

Further the decaying DC term can be expanded by applying the Taylor series and ignoring the higher order terms, we get:

$$S[m] = \sum_{h=1}^H \left[K_h \sin(\omega_h mT_s) \cos \varphi_h + K_h \cos(\omega_h mT_s) \sin \varphi_h \right] + K_{dc} - K_{dc} \gamma_{dc} mT_s + N_m \quad (6)$$

The equation which is to be estimated can be written in parametric form as:

$$\hat{S}[m] = X.H(m)^T \quad (7)$$

X is a vector of unknown parameter which is to be updated to estimate the signal and is represented by:

$$X = [K_1 \cos \phi_1 \quad K_1 \sin \phi_1 \quad \dots \quad K_h \cos \phi_h \quad K_h \sin \phi_h \quad K_{dc} \quad K_{dc} \gamma_{dc} \quad 1] \quad (8)$$

$$H(m) = [\sin(\omega_1 mT_s) \quad \cos(\omega_1 mT_s) \dots \sin(\omega_h mT_s) \quad \cos(\omega_h mT_s) \quad 1 \quad -mT_s \quad N_m] \quad (9)$$

Once the unknown parameter vector is updated using WCA, the amplitudes and phases of fundamental and h^{th} harmonic are calculated as described in equations (10-11).

$$K_h = \sqrt{\varphi_{2h}^2 + \varphi_{2h-1}^2} \quad (10)$$

$$\varphi_h = \tan^{-1} \left(\frac{\varphi_{2h}}{\varphi_{2h-1}} \right) \quad (11)$$

If signal is having the DC decaying component, parameters are computed by the expressions given in equations (12-13):

$$K_{dc} = \varphi_{2h+1} \quad (12)$$

$$\gamma_{dc} = \frac{\varphi_{2h+2}}{\varphi_{2h+1}} \quad (13)$$

3. Water Cycle Algorithm (WCA)

WCA was established by Eskandar et al. [37] and is based on the concept of water flow in the form of streams, rivers and sea. When the rain falls from clouds and snow melts from glaciers, water flows downhill in the form of streams. When streams combine at one point they generate rivers which ultimately fall into the sea. Water from lakes is evaporated and the trees also transpire the water during photosynthesis process into atmosphere to generate clouds. These clouds release water back to the earth in the form of rains and precipitation to complete the cycle which is called hydrologic cycle.

The proposed algorithm starts with raindrops as the initial population. The best rain drop which is chosen is the sea and then river and in the last rest of the drops are considered as streams. The modelling of the algorithm is given in the following lines:

To solve the N_j dimensional optimization problem with j design variables, let the rain drop array is:

$$RD = (N_1, N_2, N_3, \dots, N_j) \quad (14)$$

Where $(N_1, N_2, N_3, \dots, N_j)$ are the decision values which can be denoted as floating-point values or as a set of predefined values for discrete and continuous problems.

To start the problem, it is needed to define the population matrix of raindrops for N_j design variables and N_k population size as given:

$$Population = \begin{bmatrix} N_1^1 & N_2^1 & N_3^1 & \dots & N_j^1 \\ N_1^2 & N_2^2 & N_3^2 & \dots & N_j^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ N_1^K & N_2^K & N_3^K & \dots & N_j^K \end{bmatrix} \quad (15)$$

The raindrop's cost is evaluated using the cost function:

$$Cost_m = C_m = [N_1^m \quad N_2^m \quad N_3^m \quad \dots \quad N_j^m] \quad (16)$$

Here, $m= 1,2,3,\dots,K$. At first, K rain drops are generated and the best individuals with minimum values of rivers and sea is selected.

$$R_{best} = [No. \text{ of rivers with minimum values} + 1] \quad (17)$$

The remaining population of raindrops which forms the streams to flow into the river or directly flow into the sea is calculated as:

$$P_{drops} = [K - R_{best}] \quad (18)$$

No. of streams which flow to particular sea or rivers are dependent on the amount of flow and are calculated by the following equation:

$$S = \text{round} \left[\left\lfloor \frac{\text{Cost}_a}{\text{Cost}_m} \times P_{\text{drops}} \right\rfloor \right] \quad (19)$$

Here $a = 1, 2, 3, \dots, R_{\text{best}}$. Most of the streams flow to the rivers along the joining line choosing a random distance given below whereas some streams flow directly into the sea.

$$N \in [0, C \times y] \quad (20)$$

Here $C > 1$. C ranges between 1 and 2 with best value chosen as 2. If C is greater than one, it means that streams flow in many directions towards rivers. Y is the distance between stream and river and N represents a random value between 0 and $(0, C \times Y)$.

The fresh locations of streams and rivers may be calculated using the following equations:

$$N_S^{m+1} = N_S^m + \text{rand} \times C \times (N_R^m - N_S^m) \quad (21)$$

$$N_R^{m+1} = N_R^m + \text{rand} \times C \times (N_{\text{Sea}}^m - N_R^m) \quad (22)$$

If the stream gives the best solution, then that stream and its connecting river are exchanged and same procedure can be adopted for river and sea.

The transpired and evaporated water can cause immature convergence of the algorithm as sea water evaporates as rivers and streams to flow again to sea. This immature convergence or getting trapped in local optima can be prevented as:

$$(N_{\text{Sea}}^m - N_R^m) < y_{\text{max}} \quad \text{for } m = 1, 2, 3, \dots, R_{\text{best}} - 1 \quad (23)$$

It gives the indication that river has reached to the sea and evaporation process need to start. Y_{max} determine the best solution as for large value of it reduces the search intensity whereas lower value increases the chances of search intensity to be near the sea. The value of Y_{max} decreases as:

$$y_{\text{max}}^{m+1} = y_{\text{max}}^m - \frac{y_{\text{max}}^m}{\text{Max iteration}} \quad (24)$$

After the evaporation process the rains starts and new streams are formed at different locations. The new location is computed as:

$$N_S^{\text{new}} = LL + \text{rand} \times (UL - LL) \quad (25)$$

LL and UL are the lower and upper limits defined by the problem respectively. The best raindrop is picked as river and the others are supposed to form new streams which flow towards river or directly to the sea.

To increase the convergence rate and performance of the algorithm, following equation is applied to constrained

optimization problems as it motivates to yield new streams which directly flow to the sea.

$$N_S^{\text{new}} = X_{\text{sea}} + \mu \times \text{randn} \times (1, N_j) \quad (26)$$

The μ defines the range search near sea for optimum solution and the best value for μ is set to 0.1. The larger value of μ increases the chances to deviate from the best region. The flow chart of WCA is displayed in Fig. 1.

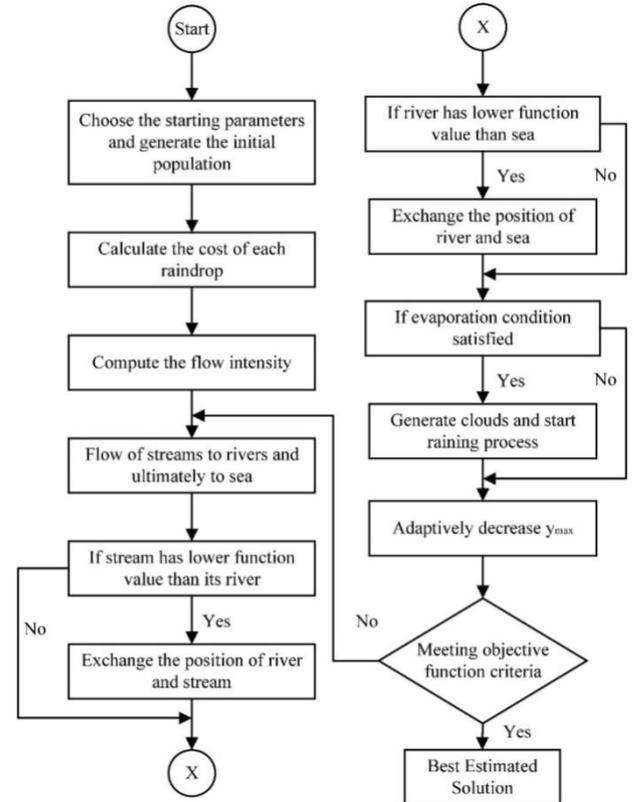


Fig. 1: Flow chart of WCA.

4. Harmonics Estimation using Proposed WCA-LS

To estimate the desired signal, a matrix of N_j raindrops is initialized according to the number of harmonics required as mentioned in unknown parameter vector N . The prime objective of harmonics estimation problem is to minimize the Residual Sum of Squares (RSS) as objective and fitness function. The application of proposed WCA-LS for harmonics estimation problem is represented by Pseudo code as given below:

1. Initialization of WCA parameters:

- Number of Rivers and Sea with minimum value (R_{best}), Y_{max} , Maximum iteration, K
- Generate the initial Population matrix, raindrops, rivers and sea using Eqs. 15, 17 and 18.
- Compute the cost and water flow intensity using Eqs. 16 and 19.

Loop (iter:1→maximum Iterations)

- Flow of streams to the rivers and rivers to the sea using Eqs. 21 and 22.

Loop (iter:1→Number of Rivers)
Loop (iter:1→Number of Streams -1)
2. Evaluate fitness values for each stream using:

$$FIT = \min \sum (S - \hat{S})^2 \quad (27)$$

IF (FIT(Stream)<FIT(River))
Swap the position of river and stream
IF (FIT(River)<FIT(Sea))
Swap the position of river and sea
End
End
End of Loop
End of Loop
Loop (iter:1→Number of Rivers)
3. Evaluate again fitness values for each River
4. Check the evaporation condition and start raining process to form new streams
Loop (iter:1→Number of Rivers)
IF (Distance between Sea and river positions is less than Y_{max})
Loop (iter:1→Number of Streams-1)
Define new streams using eq. 25
End of Loop
End
End of Loop
Loop (iter:1→Number of Streams-1)
IF (Distance between Sea and stream positions is less than Y_{max})
Loop (iter:1→Number of Streams)
Define new streams using eq. 25
End of Loop
End
5. Adoptively decrease Y_{max} using eq. 24
6. Estimate the best desired signal
End of Loop
Computation of amplitudes and phases of the estimated signal
End of Loop (iter)
7. Estimate the desired signal
8. Computation of amplitudes and phases of the estimated signal

5. Simulation Results and Discussion

To validate the performance of proposed WCA-LS, the harmonics estimation of different test signals has been carried out. Most of the test signals are being used in literature for comparative analysis of harmonics estimation techniques. First of all, WCA-LS has been applied to estimate the integer harmonics in the presence of DC decaying offset. The strength of the proposed WCA-LS has been authenticated by extracting the sub and inter harmonics in the power system signal in non-noisy as well as noisy environment. The uniform and Gaussian noises have been added to the test signals signifying the WCA-LS working in highly non-linear and dynamic search space. The application of WCA-LS for harmonics estimation has been further extended to real time examples of Axial Flux Permanent Magnet Synchronous Generator (AFPMSG).

The WCA-LS has been evaluated on the basis of three statistical parameters: Residual Sum of Squares (*RSS*), Performance Index (*PER*) and Mean Square Error (*MSE*). The difference between power signal and estimated signal yields residuals (*RES*) as following:

$$RES = S - \hat{S} \quad (28)$$

The basic objective function of the problem is to minimize the *RSS* in highly non-linear and dynamic search domain [38]. The value of estimated *RSS* is specified by:

$$RSS = \sum (S - \hat{S})^2 \quad (29)$$

Most of the literature appraises the strength of the estimation technique based on *PER* [39]. This is the parameter for comparative analysis of different estimation techniques. *PER* is given as:

$$PER = \frac{\sum (S - \hat{S})^2}{\sum S^2} \times 100\% \quad (30)$$

One of the statistical parameters is *MSE* which can be intended from power and estimated signals [38]. The mathematical model to compute the *MSE* is given by:

$$MSE = \frac{\sum (S - \hat{S})^2}{n} \quad (31)$$

The performance evaluation as demonstrated by three parameters *RSS*, *PER* and *MSE* over all iterations have been shown graphically for each and every case study presented in this section. The performance parameters decrease tremendously as iterations increase and harmonic estimation is being congregated to a constant level. This behavior of optimizing the estimation of harmonics is supported by application of proposed WCA-LS which can be realized from graphical results (semilogy) in this section for each case study. The simulations for each case study are performed on Laptop: Make DELL Inspiron, Intel Pentium CPU B950 @ 2.10 GHz processor, 2 GB RAM and 32 bit operating system (Windows 8). The proposed WCA-LS is programmed in MATLAB and simulations are run on MATLAB R2014a[®]. The different parameters of WCA-LS are set according to the nature of case study and its vibrant behavior.

5.1 Integral Harmonics Estimation of Power System in the Presence of DC Decaying Offset and Additive Random Noise

The test signal used for integral harmonics estimation is basically the characteristic signal generated by Variable Frequency Drives (VFDs), electric arc furnaces and power electronic based equipment in industry [40]. An imitated signal is used in [30] has been generated for harmonics extraction. The generated signal consists of DC decaying

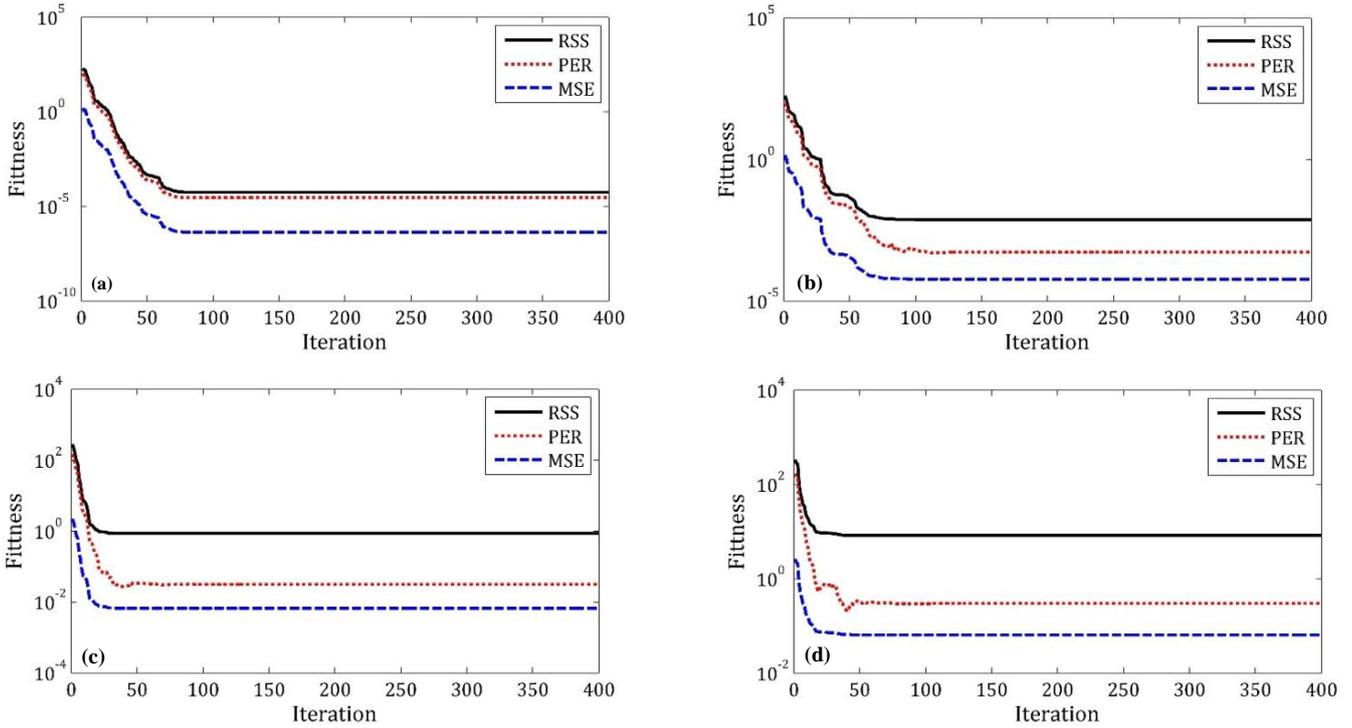


Fig. 2: Convergence characteristics of WCA-LS while estimating harmonics: (a) No noise, (b) 40 dB SNR, (c) 20 dB SNR, (d) 10 dB SNR.

offset of $0.5 \cdot \exp(-5t)$ in the presence of additive random noise. The harmonic contents of actual signal are given in Table 1.

Table 1: Harmonic contents of test signal deployed for integral harmonic estimation.

Harmonic Order	Frequency (Hz)	Amplitude (p.u.)	Phase (deg)
1	50	1.5	80
3	150	0.5	60
5	250	0.2	45
7	350	0.15	36
11	550	0.1	30

The continuous time signal has been sampled and discretized according to Nyquist criterion considering 64 samples per cycle. The sampling frequency of signal is considered to be 3.2 kHz. The proposed WCA-LS has been applied to the corrupted signal with integral harmonics and DC decaying offset. The three signals have been constituted from test signal considering noise injections of 40, 20 and 10 dB signal-to-noise ratios (SNRs).

The simulation for high optimal extraction of harmonics have been executed on four signals: one actual signal with no noise and three signals with specified SNRs. The proposed WCA-LS is applied allowing for number of 50 raindrops and maximum of 400 iterations. Evaporation condition constant is set to be 1×10^{-16} . Fig. 2(a) shows the convergence of evaluation parameters for the case of estimating integral harmonics in non-noisy environment.

Further the signal is injected with noise of specified levels for three cases: 40, 20 and 10 dB SNRs. The 40 dB SNR level of noise is the lowest and Fig. 2(b) displays the good performance for the harmonics estimation. The signal is corrupted with higher value of noise 20 dB SNR, proposed WCA-LS is run to estimate the signal and performance is evident from Fig. 2(c). At last, the signal is contaminated with highest value of noise 10 dB SNR and convergence of problem is exposed by Fig. 2(d). From Fig. 2, it is obvious that WCA-LS has been converged within first 100 iterations and becomes smooth for next 300 iterations. The actual signals, estimated signals and noisy signals are presented in Fig. 3 for non-noisy as well as for three cases of noisy conditions.

After estimating the harmonics, the residuals are computed and expressed by Fig. 4 for non-noisy condition. The extraction of harmonics involves estimation of amplitudes as well as phases for harmonic contents. The convergence of proposed WCA-LS over all iterations for each individual amplitude and phase is publicized in Fig. 5.

The proposed WCA-LS is equated with previous techniques presented in literature for estimating harmonics present in the power signals. The comparative assessment is listed in Table 2 which reveals robustness of proposed WCA-LS for harmonics estimation in terms of estimating the amplitudes and phases, percentage errors in estimating the amplitudes and phases and computational time. From the numerical results, it is obvious that proposed WCA-LS is superior to other techniques for harmonic estimation and present the promising results.

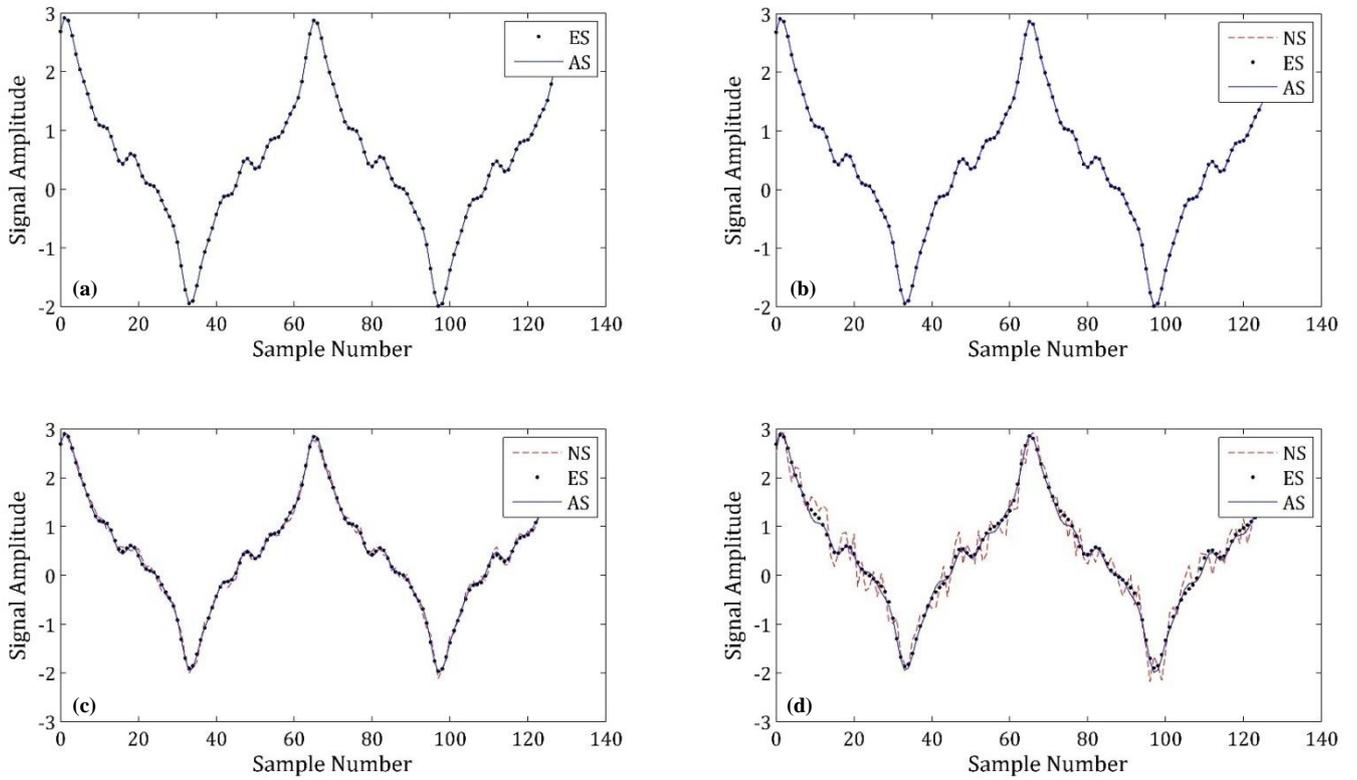


Fig. 3: Comparison of estimated and power signals: (a) No noise, (b) 40 dB SNR, (c) 20 dB SNR, (d) 10 dB SNR.

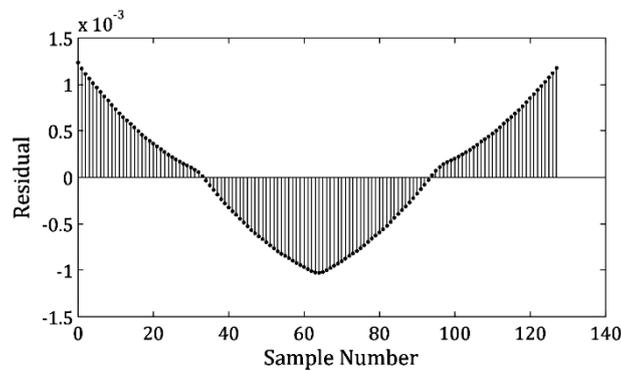


Fig. 4: Residual errors between samples of estimated and non-noisy power signals.

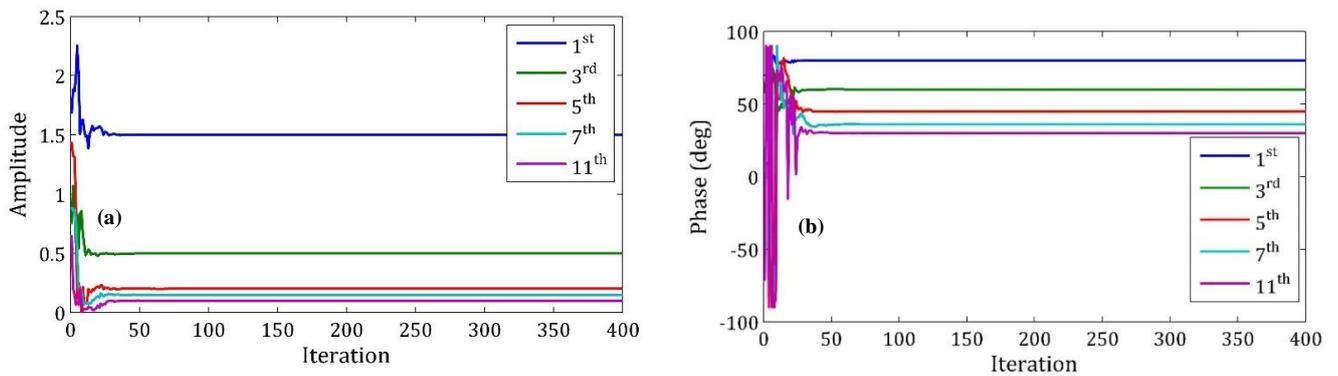


Fig. 5: Convergence characteristics while estimating individual (a) amplitudes of harmonics, (b) phases of harmonics.

Table 2: Relative performance revealed by different techniques for integral harmonics estimation.

Algorithm	Parameters	Fundamental	3rd	5th	7th	11th	Computation time (s)
Actual	Frequency	50	150	250	350	550	–
	Amplitude (V)	1.5	0.5	0.2	0.15	0.1	
	Phase (deg)	80	60	45	36	30	
BFO [40]	Amplitude (V)	1.4878	0.5108	0.1945	0.1556	0.1034	10.931
	Error (%)	0.8147	2.1631	2.7267	3.7389	3.4202	
	Phase (deg)	80.4732	57.9005	45.8235	34.5606	29.127	
	Error (%)	0.4732	2.0995	0.8235	1.4394	0.873	
F-BFO-LS [10]	Amplitude (V)	1.488	0.5103	0.198	0.1545	0.1028	10.532
	Error (%)	0.8	2.06	1	3	2.8	
	Phase (deg)	80.42	58.1	45.75	34.73	29.358	
	Error (%)	0.42	1.9	0.75	1.27	0.642	
BFO-RLS [40]	Amplitude (V)	1.4942	0.4986	0.2018	0.1526	0.0986	9.345
	Error (%)	0.384	0.2857	0.9021	1.7609	1.746	
	Phase (deg)	80.3468	58.5461	45.6977	34.8079	29.9361	
	Error (%)	0.3468	1.4539	0.6977	1.1921	0.0639	
BBO-RLS [39]	Amplitude (V)	1.4953	0.5004	0.2008	0.149	0.0999	5.852
	Error (%)	0.3104	0.08501	0.42031	0.19605	0.08302	
	Phase (deg)	79.7888	59.541	45.5153	36.1165	30.0124	
	Error (%)	0.264	0.5661	1.1452	0.3238	0.0415	
WCA-LS	Amplitude (V)	1.500	0.500	0.200	0.150	0.100	1.753
	Error (%)	0.01503	0.00443	0.00328	0.00188	0.00102	
	Phase (deg)	80.0017	60.0015	45.0019	36.0015	30.0010	
	Error (%)	0.00209	0.00249	0.00425	0.00420	0.00347	

5.2 Harmonics Estimation of Power System Signal including Sub and Inter Harmonics in the Presence of Additive Random Noise

The signal of integral harmonic estimation is further dishonored with sub and inter harmonics in the presence of additive random noise. The problem of considering sub and inter harmonics in harmonics estimation yields a complex and non-linear search space. First the signal is despoiled with sub harmonic of $0.505 < 75^\circ$ (20 Hz) and inter harmonics of $0.25 < 65^\circ$ (180 Hz) and $0.35 < 20^\circ$ (230 Hz).

The resulting signal is estimated in non-noisy as well as in noisy environment of 40, 20 and 10 dB SNRs. Fig. 6 shows the performance evaluation of estimation using proposed WCA-LS. The superimposed actual and estimated signals are demonstrated by Fig. 7 for non-noisy and noisy conditions. The proposed WCA-LS is run allowing for 50 raindrops moving in search space and maximum of 400 iterations. From Fig. 6(a), it is apparent that performance parameters continue to decrease drastically up to the order of 10^{-18} and maximal number of iterations reached.

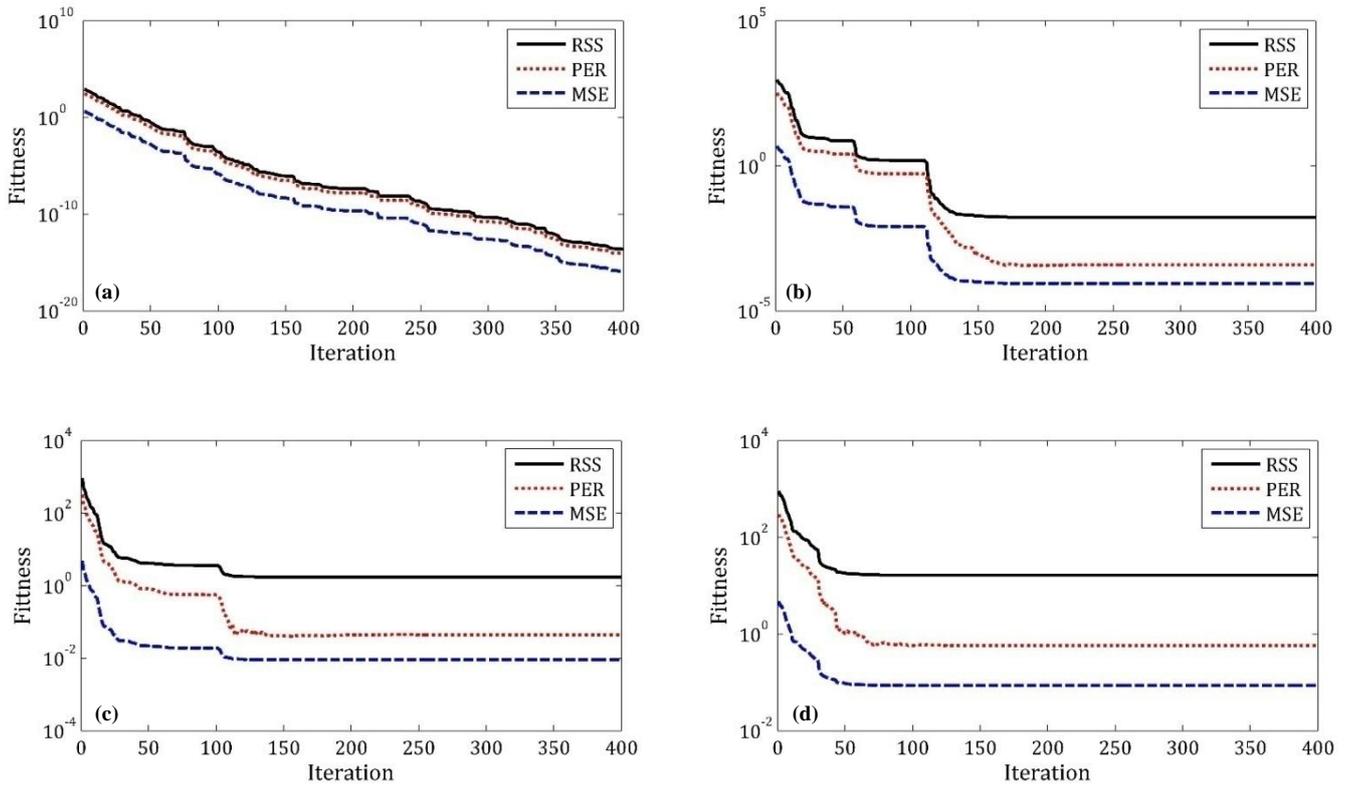


Fig. 6: Convergence characteristics of WCA-LS while estimating harmonics: (a) No noise, (b) 40 dB SNR, (c) 20 dB SNR, (d) 10 dB SNR.

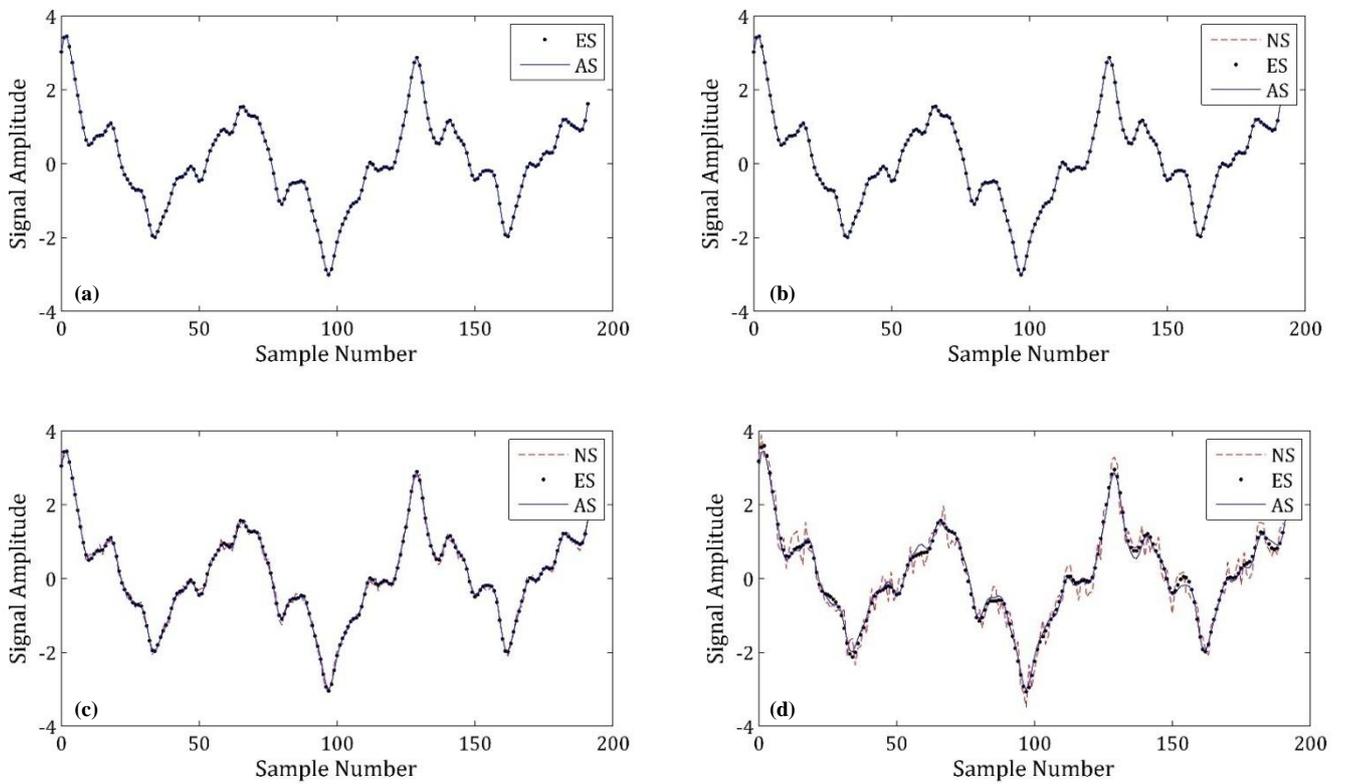


Fig. 7: Comparison of estimated and power signals: (a) No noise, (b) 40 dB SNR, (c) 20 dB SNR, (d) 10 dB SNR.

Table 3: Relative performance unveiled by different techniques for integral harmonics estimation including sub and inter harmonics.

Algorithm	Parameters	Sub	Fund	3rd	Inter-1	Inter-2	5th	7th	11th	Computation time (s)
Actual	Frequency	20	50	150	180	230	250	350	550	–
	Amplitude (V)	0.505	1.5	0.5	0.25	0.35	0.2	0.15	0.1	
	Phase (deg)	75	80	60	65	20	45	36	30	
F-BFO-LS [10]	Amplitude (V)	0.521	1.489	0.489	0.261	0.371	0.208	0.1468	0.1019	13.253
	Error (%)	3.247	0.733	0.489	4.4	6	4	2.13	1.9	
	Phase (deg)	74.61	79.86	61.16	64.33	19.723	47.22	36.658	30.52	
	Error (%)	0.388	0.14	1.16	0.67	0.277	2.22	0.658	0.52	
BFO-RLS [40]	Amplitude (V)	0.511	1.5029	0.4921	0.2581	0.3639	0.2009	0.1479	0.1015	12.837
	Error (%)	1.19	0.1952	1.5887	3.2372	3.9651	0.4541	1.4149	1.48	
	Phase (deg)	74.81	79.9148	59.076	65.3445	19.8677	46.278	36.4473	30.0643	
	Error (%)	0.183	0.0852	0.924	0.3445	0.1323	1.2783	0.4473	0.0643	
ABC-LS [41]	Amplitude (V)	0.506	1.49692	0.4912	0.24106	0.33701	0.4988	0.14707	0.09845	8.9543
	Error (%)	1.225	0.2052	1.7532	3.5745	3.7125	0.5526	1.9557	1.5545	
	Phase (deg)	74.853	80.0733	59.4211	64.763	19.965	45.2916	35.7993	29.9773	
	Error (%)	0.1954	0.09164	0.9648	0.3645	0.1725	1.5485	0.5575	0.0754	
FA-RLS[28]	Amplitude (V)	0.499	1.4984	0.5004	0.2457	0.3497	0.2009	0.1497	0.0999	6.7543
	Error (%)	1.18811	0.10667	0.08	1.72	0.08571	0.45	0.2	0.1	
	Phase (deg)	74.931	79.948	59.541	65.203	19.973	45.523	36.128	30.0126	
	Error (%)	0.0912	0.0642	0.7643	0.3125	0.1305	1.1642	0.3572	0.0421	
BBO-RLS [39]	Amplitude (V)	0.4943	1.4984	0.5003	0.2458	0.3497	0.2008	0.1485	0.0999	6.7525
	Error (%)	1.1255	0.10455	0.0785	1.65055	0.07875	0.4452	0.9557	0.1	
	Phase (deg)	74.9321	79.95	59.5228	65.1706	19.9775	45.52	36.1179	30.0123	
	Error (%)	0.0905	0.0625	0.7452	0.2625	0.1125	1.1565	0.3275	0.041	
WCA-LS	Amplitude (V)	0.505	1.500	0.500	0.249	0.350	0.199	0.149	0.100	1.8424
	Error (%)	2.26×10^{-7}	1.03×10^{-7}	1.68×10^{-6}	3.25×10^{-7}	1.06×10^{-6}	9.53×10^{-7}	2.16×10^{-6}	2.37×10^{-6}	
	Phase (deg)	75.00	80.00	60.00	65.00	20.00	45	36.00	30.00	
	Error (%)	5.49×10^{-7}	5.24×10^{-8}	1.07×10^{-6}	5.88×10^{-7}	7.48×10^{-6}	1.50×10^{-9}	3.55×10^{-6}	4.29×10^{-6}	

The proposed WCA-LS is compared with existing techniques present in literature for estimating the harmonics present in the signals. The comparative assessment is listed in Table 3 and discloses the robustness of proposed WCA-LS for harmonics estimation in terms of

estimating the amplitude and phases, percentage errors in estimating the amplitudes and phases and computational time. From the numerical results, it is obvious that proposed WCA-LS is superior to other practices for harmonic estimation and bestow the auspicious results.

Table 4: Comparison of performance index (PER) parameter computed by application of different algorithms.

Algorithm	No noise	40 dB	20 dB	10 dB
GA-LS [9]	0.1576	0.183	1.2037	10.653
PSOPC-LS [42]	0.1236	0.157	0.9546	7.3645
BFO [40]	0.1178	0.138	0.8073	5.2549
F-BFO-LS [10]	0.1054	0.112	0.8021	5.1864
BFO-RLS [40]	0.087	0.092	0.787	4.5482
ABC-RLS [41]	0.0752	0.0895	0.6554	4.2545
FA-RLS [28]	0.0752	0.0785	0.561	3.9745
BBO-RLS [39]	0.0658	0.075	0.5735	3.8555
WCA-LS	7.99×10^{-15}	0.00041169	0.025264	0.46455

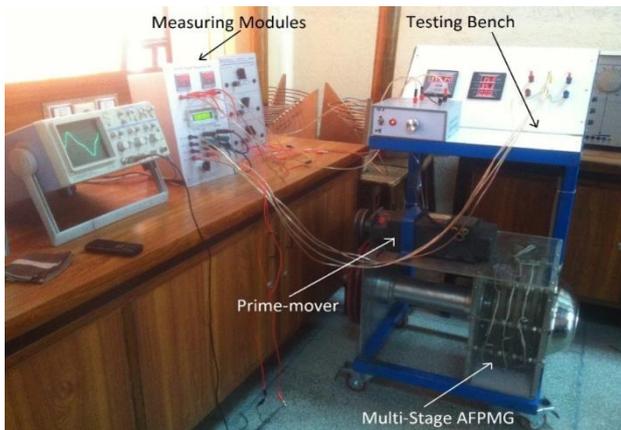


Fig. 8: Multi-stage AFPMSG testing bench.

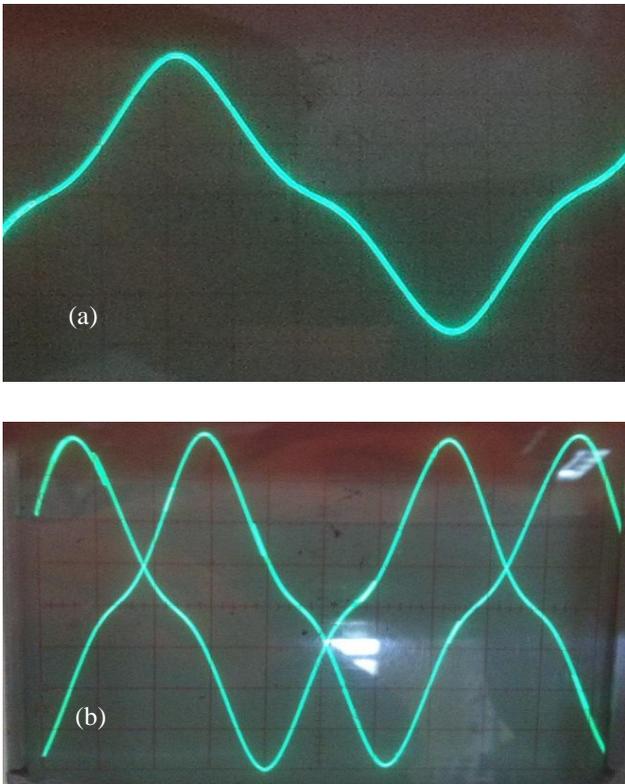


Fig. 9: (a) 1-phase voltage waveform of AFPMSG model, (b) Voltage waveform of two phases of AFPMSG model

The sturdiness of the proposed WCA-LS becomes evident in the noisy conditions as well. Even noise at 10 dB SNR is the highest and WCA-LS harmonic estimation is comparable with other techniques presented in literature in terms of PER. The numerical results presented in the Table 4 signify the proposed WCA-LS in extensive noisy conditions.

5.3 A Real Time Example of Output Voltage Waveform Generated by Axial Flux Permanent Magnet Generator (AFPMSG)

Renewable energy technologies are becoming more popular in recent decades because of ever increasing energy demand, prices of fossil based fuels, pollution of conventional energy producing sources [43]. Among numerous electrical energy production sources wind is the cheaper source [44]. The Axial Flux Permanent Magnet Synchronous Generators (AFPMSGs) are replacing Radial Flux Permanent Magnet Generators (RFPMSGs) in modern wind turbine technologies because of unique features unveiled by AFPMSG. This type of AFPMSG is advantageous due to higher torque-to-weight ratio, maximum power density, high efficiency, absence of cogging torque losses, compact structure, light weight and small operating shaft speed [45-47]. The shape of permanent magnet strongly affects the output voltage waveform generated by AFPMSG. In literature, a 3-phase, multi-stage AFPMSG [48] was designed whose voltage waveform is taken as power signal for harmonics estimation. The voltage waveform of AFPMSG has been recorded by Oscilloscope at sampling frequency of 10kHz. The model of AFPMSG is shown in Fig. 8 and output voltage for two phases is shown in Fig. 9. The robust WCA-LS is applied for harmonics estimation of the voltage signal for first 15 integral harmonics. The problem of estimation is executed for 600 maximal iterations in this case for 50 number of raindrops wandering in the search space. Fig. 10 expresses the performance parameters for estimation of harmonics over the iterations from which it is evident that problem converges below 300 iterations. Fig. 11 shows the comparison of actual and estimated signals. Fig. 12 displays the amplitude of first 15 integer harmonics. Table 5 highlights the statistical parameters computed after simulation run.

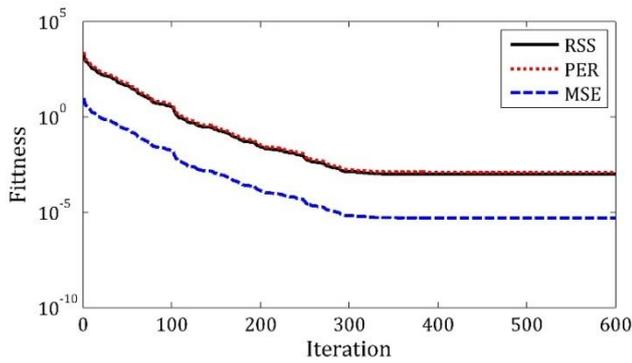


Fig. 10: Convergence characteristics of WCA-LS while estimating harmonics in voltage waveform of AFPMSG.

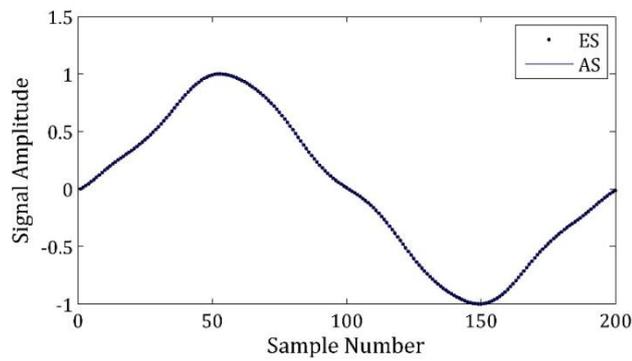


Fig. 11: Comparison of estimated and actual voltage signal.

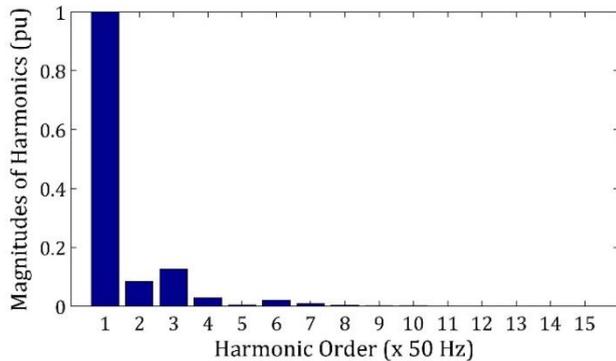


Fig. 12: Amplitude of First 15 Integer harmonics.

Table 5: Performance evaluation parameters for simulation.

Performance parameter	Value
RSS	0.00098747
PER	0.0012572
MSE	4.94×10^{-06}
Computation time (s)	2.257

6. Conclusions

A heuristic WCA-LS has been proposed for effective estimation of both phases and amplitudes from noisy power signals. Results are validated both in terms of accuracy (RSS, MSE, PER) and computational time.

Different theoretical and real time case studies are explored to evaluate the performance of proposed approach. Integer inter, and sub harmonics are extracted from power signals at different uniform noise levels (40 dB, 20 dB, 10 dB). Results and discussion section clearly signify the robustness of WCA-LS in harmonic estimation when compared to GA, PSOPC-LS, BFO, FBFO-LS, ABC-LS, FA-RLS and BBO-RLS. The application of WCA-LS has been further extended to real time output voltage waveform of AFPMSG. This diversity of WCA-LS exhibits the versatility of algorithm in solving nonlinear and complex optimization problems.

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