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# Robust Extraction of Harmonics using Heuristic Advanced Gravitational Search Algorithm-based Least Square Estimator

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ABSTRACT

*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 algorithm of Advanced Gravitational Search Algorithm-based Least Square (AGSA-LS) for estimation of harmonics present in time varying noisy power signals. Advanced Gravitational Search Algorithm (AGSA) is a population based algorithm which realizes the concepts of exploitation and exploration to find global optimal in search space under consideration. In AGSA, Newtonian law of gravity and laws of motion are explored to optimize mathematically the location of planets in search space. 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 current signal drawn by LED lamp. The proposed AGSA-LS delivers promising results compared to 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 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 which are either integer multiples of fundamental frequency or non-integer multiples termed as inter harmonics. Inter harmonics having frequency less than fundamental are recognized as sub harmonics. 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 all of 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].

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, 12]. 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 [13, 14]. 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 mother 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 also are incorporated to successfully approximate the harmonics out of distorted power signals [6, 15].

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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 [16, 17]. 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 [16]. 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 less computational time compared to KF and Ensemble-KF (En-KF) [18]. Accuracy of proposed modified KF is apparent since distorted power waveform belongs to large paper industry. Aside KF, other statistical approaches being utilized are LS and LMS [2, 19]. Kwong and Johnston [20] 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] have 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 similarity 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 [21]. Bettayeb et al. [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 show 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. [22] 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 this 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.

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 et al. [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 performs 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. [23] 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. [24] 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. [25] have carried out 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. [26] 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 [23] and ABC-LS approach [27]. Singh et al. [28] 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 compared to other soft computing techniques like ABC-RLS [27] 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 [29, 30].

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. Advanced gravitational search algorithm (AGSA) 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 AGSA to incorporate least square signal attribute. A hybrid method of AGSA 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 ASGA-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 makes 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:

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

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

$$\omega_h = h \times 2\pi f_1 \tag{2}$$

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

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

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:

$$S(mT_s) = \sum_{h=1}^{H} \begin{bmatrix} K_h \sin(\omega_h mT_s + \varphi_h) \\ + K_{dc} \exp(-\gamma_{dc} mT_s) + N_{mT_S} \end{bmatrix} \quad (4)$$

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

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

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

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

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:

$$\begin{aligned} X = [&K_1 \cos\phi_1 \quad K_1 \sin\phi_1 \quad \ldots\ldots \\ &K_h \cos\phi_h \quad K_h \sin\phi_h \quad K_{dc} \quad K_{dc}\gamma_{dc} \quad 1] \end{aligned} \quad (8)$$

$$\begin{aligned} H(m) = [&\sin(\omega_1 mT_s) \quad \cos(\omega_1 mT)\ldots \\ &\sin(\omega_h mT_s) \quad \cos(\omega_h mT) \quad 1 \quad -mT_s \quad N_m] \end{aligned} \quad (9)$$

Once the unknown parameter vector is updated using AGSA, 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 DC decaying component, parameters are computed by the expressions given in equations (12-13):

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

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

## 3. Advanced Gravitational Search Algorithm (AGSA)

AGSA is a population based algorithm which realizes the concepts of exploitation and exploration. The algorithm was established by Rashdi et. al. [31] and is based upon the law of gravity and laws of motion. The performance analysis of different parameters and function optimization is presented elsewhere [3]. The algorithm is chosen to estimate the harmonics in power system due to its high performance as compared to other heuristic algorithms.

In the universe, all the planets/objects attract each other according to law of gravity and move toward each other. The masses of the planets may differ and accordingly their motion toward each other is also varied. The velocity of planets with less masses is more as compared to a planet with large mass. All the smaller masses rush towards the large mass hence it presents a global optimum solution and avoids trapping of the local optimums using exploration at the beginning. The modelling of the algorithm is given in the following lines.

$$\begin{aligned} &P_f = (p_f^1, p_f^2, p_f^3, \ldots\ldots\ldots p_f^b, \ldots\ldots\ldots p_f^F,,) \\ &for \quad f = 1, 2, 3, \ldots\ldots\ldots F \end{aligned} \quad (14)$$

Where $p^F{}_f$ is the position of $f^{th}$ planet in the $b^{th}$ dimension.The force which acts on mass '$f$' from any mass '$g$' at any particular time '$t$' is given by

$$F_{fg}^b(t) = G(t) \frac{M_{ag}(t) \times M_{pf}(t)}{R_{fg}(t) + \eta} \times (p_g^b(t) - p_f^b(t)) \quad (15)$$

Where $M_{pf}$is the passive gravitational mass of planet '$f$', $M_{ag}$ the active gravitational mass of planet '$g$', $G(t)$ the gravitational constant at time '$t$', $\eta$ the small distance parameter, $G(t)$ a function of time and initial value $G_o$. The value of $G(t)$ reduces with the passage of time to govern the accuracy of search. $R_{fg}(t)$ represents the Euclidian spacing between two planets as:

$$R_{fg}(t) = \left\| P_f(t), P_g(t) \right\|_2 \quad (16)$$

To add the un-deterministic characteristics in the algorithm the accumulating force which is exerted on planet '$f$' in b$^{th}$ dimension can assuming a weighted sum of the components, in $b^{th}$ dimension of force from other planets is given as:

$$F_f^b(t) = \sum_{g=1, g\neq f}^{F} rand_g F_{fg}^b(t) \quad (17)$$

The performance of AGSA can further be improved if we properly control exploitation and exploration steps. In this case, only the Pfinest planet will attract others. In the beginning the value of $P_{finest}$ will be $P_o$ which decreases with time. All the planets exert forces in the beginning and with the passage of time $P_{finest}$ decreases linearly and then only one planet will be there which will apply force on others. The above equation can be further modified as:

$$F_f^b(t) = \sum_{g \in P_{finest},\, g \neq f}^{F} rand_g F_{fg}^b(t) \tag{18}$$

Where $P_{finest}$ is the set of first '$P$' planets with the largest mass and best fitness value. Planet '$f$' at time '$t$' moves with acceleration $a_i$ in $b^{th}$ direction according to law of motion is given as:

$$\alpha_f^b(t) = \frac{F_f^b(t)}{M_{if}(t)} \tag{19}$$

Where $M_{if}$ is the inertial mass of $f^{th}$ planet. Next the velocity of the planet is modelled as a sum of fraction of its current velocity and its acceleration.

$$U_f^b(t+1) = rand_f \times U_f^b(t) + \alpha_f^b(t) \tag{20}$$

Next position of planet could be calculated as:

$$p_f^b(t+1) = p_f^b(t) + U_f^b(t+1) \tag{21}$$

To calculate the masses of the planets, fitness values are used. The planet which move slowly and have large attractions are considered to be the best planet. The finest and nastiest values for a minimization problems are defined as:

$$finest(t) = \min_{g \in \{1,\ldots F\}} fit_g(t) \tag{22}$$

$$nastiest(t) = \max_{g \in \{1,\ldots F\}} fit_g(t) \tag{23}$$

For a maximization problems, the roles of above equations are reversed.

$$finest(t) = \max_{g \in \{1,\ldots F\}} fit_g(t) \tag{24}$$

$$nastiest(t) = \min_{g \in \{1,\ldots F\}} fit_g(t) \tag{25}$$

Inertial and gravitational masses are updated using the map of the fitness by the following equations:

$$\begin{aligned} M_{pf} &= M_{af} = Mi_f = M_f \\ f &= 1,2,3\ldots\ldots\ldots F \end{aligned} \tag{26}$$

$$m_f(t) = \frac{fit_f(t) - nastiest}{finest(t) - nastiest(t)} \tag{27}$$

$$M(t) = \frac{m_f(t)}{\sum_{g=1}^{F} m_g(t)} \tag{28}$$

$Fit_f(t)$ represents the fitness value of the planet '$f$' at time '$t$'. The power harmonic estimation problem using the AGSA is described in Fig. 1 as flowchart.

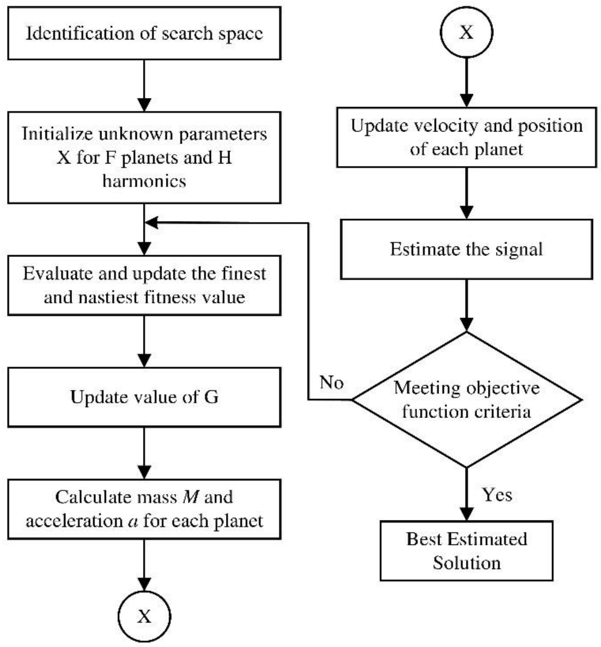


Fig. 1: Flow chart of AGSA

## 4. Harmonics Estimation using Proposed AGSA-LS

To estimate the desired signal, a matrix of '$F$' planets is initialized according to the number of harmonics required as mentioned in unknown parameter vector $X$. 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 AGSA-LS for harmonics estimation problem is represented by Pseudo code as given below:

---

1. Initialization of AGSA parameters:
    - Number of planets ($F$)
    - Maximum iterations ($T$)
    - Gravitational constant ($G_o$)
    - Decaying constant for $G$ ($\alpha$)
2. Initialization of power signal parameters:
    - Population matrix ($X$)
    - Velocity matrix ($U$)
    - System structure matrix ($H$)

**Loop (iter:1→T)**

3. Evaluate fitness values for each planet:

Loop ($f$:$1 \rightarrow F$)

$$FIT = \min \sum (S - \hat{S})^2 \tag{29}$$

End of Loop ($f$)

4. Segregate the minimum and maximum fitness values:

---

- finest(iter) = min(FIT)
  - *nastiest(iter) = max(FIT)*
  - Find the best planet for each iteration:

    *best(iter) = min(FIT)*

5. Calculate mass of each planet using Eqs. (27, 28)
6. Update gravitational constant G using following equation

$$G = G_o \exp(-\alpha \frac{iter}{T}) \quad (30)$$

7. Calculate acceleration in gravitational field:

   Loop (*f:1→F*)

   Loop (*b:1→B*)
   - Computation of force *F(iter, f, b)* using Eq. (15)
   - Calculate the force acting on planets *F(f, b)* using Eq. (18)

   End of Loop (*b*)

   End of Loop (*f*)
   - Calculate acceleration *a(f, b)* using Eq. (19)

8. Update position and velocity of planets using Eqs. (20, 21)

**End of Loop (iter)**

9. Estimate the desired signal
10. Computation of amplitudes and phases of the estimated signal

## 5. Simulation Results and Discussion

To validate the performance of proposed AGSA-LS, the harmonics estimation of different test signals was carried out. Most of the test signals have been used in literature for comparative analysis of harmonics estimation techniques. First of all, AGSA-LS has been applied to estimate the integer harmonics in the presence of DC decaying offset. The integer harmonics were those which represent the integer multiples of fundamental frequency [32]. The strength of the proposed AGSA-LS was authenticated by extracting the sub and inter harmonics in the power system signal in non-noisy as well as noisy environment. The harmonics with frequency lower than fundamental are known as sub harmonics and those demonstrating the non-integer multiples of fundamental are referred to as inter harmonics [33]. The uniform and Gaussian noises were added to the test signals signifying the AGSA-LS working in highly non-linear and dynamic search space. The application of AGSA-LS for harmonics estimation has been further extended to real time examples of Axial Flux Permanent Magnet Generator (AFPMG) and LED lamp.

The performance of the proposed AGSA-LS was 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*) is as follows:

$$RES = S - \hat{S} \quad (31)$$

The basic objective function of the problem is to minimize RSS in the highly non-linear and dynamic search domain [34]. The value of estimated *RSS* is specified by equation (32):

$$RSS = \sum (S - \hat{S})^2 \quad (32)$$

Most of the literature appraises the strength of the estimation technique based on *PER* [35]. This is the parameter for comparative analysis of different estimation techniques. *PER* is given in equation (33):

$$PER = \frac{\sum (S - \hat{S})^2}{\sum S^2} \times 100\% \quad (33)$$

One of the statistical parameters is *MSE* which can be intended from power and estimated signals [34]. The mathematical model to compute *MSE* is given by:

$$MSE = \frac{\sum (S - \hat{S})^2}{n} \quad (34)$$

The performance evaluation as demonstrated by three parameters *RSS*, *PER* and *MSE* over all iterations are shown graphically for each and every case study presented in this section. The performance parameters decrease tremendously as iterations increase and harmonic estimation is congregated to a constant level. This behaviour of optimizing the estimation of harmonics is supported by application of proposed AGSA-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 AGSA-LS is programmed in MATLAB and simulations are run on MATLAB R2014a®. The different parameters of AGSA-LS are set according to the nature of the case study and its vibrant behavior.

### *5.1 Harmonics Estimation in Voltage Signal of a Full-wave, Six-pulse Bridge Rectifier*

The voltage signal from a full-wave, six-pulse bridge rectifier was considered for extraction of harmonics in the presence of additive noise [23]. A very small version of power system is shown in Fig. 2 which consists of two buses: a generation bus and a load bus. The load is fed through a bridge rectifier and test signal as power signal is taken into consideration from load bus. The contents of power signal are listed in Table 1.

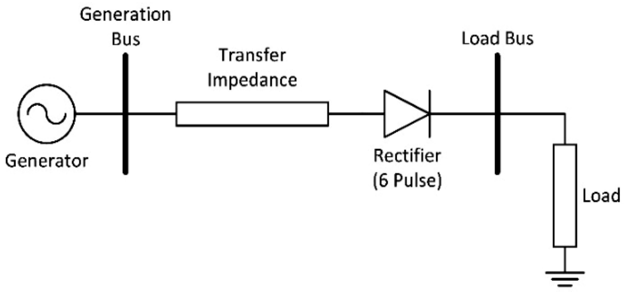


Fig. 2: Two-bus small power system

Table 1: Harmonic contents of test signal

| Harmonic Order | Frequency (Hz) | Amplitude (p.u.) | Phase (deg) |
|---|---|---|---|
| 1 | 50 | 0.95 | -2.02 |
| 5 | 250 | 0.09 | 82.1 |
| 7 | 350 | 0.043 | 7.9 |
| 11 | 550 | 0.03 | -147.1 |
| 13 | 650 | 0.033 | 162.6 |

The power signal consisting of above mentioned harmonic contents is generated in non-noisy as well as noisy milieu considering 64 samples per cycle of 50 Hz. In noisy environment, two types of noises are added to the power signal: Uniform and Gaussian noise. The levels deliberated for additive uniform noise for power signals are 20, 10 and 0 dB SNRs. The power signal is estimated by running AGSA-LS allowing maximal of 200 iterations and 50 number of planets in non-noisy and noisy conditions when uniform random noise is added. Fig. 3 displays the convergence of AGSA-LS for non-noisy and noisy conditions. It is palpable that AGSA-LS minimizes the evaluation parameters tremendously up to the order of $10^{-18}$ as observed from Fig. 3(a). The uniform noise of 10 dB noise is inserted in power signal and estimation through AGSA-LS is run for maximal number of iterations as shown in Fig. 3(c). AGSA-LS is further employed to estimate the contaminated power signal at the highest level of noise 0 dB SNR. From the convergence results shown in Fig.3(b, c and d), it is noticeable that estimation comes to constant level below 100 iterations which reveal the strength of proposed AGSA-LS. Fig. 4 demonstrates the estimated signal in the presence of different levels of uniform noise (SNRs). The convergence of amplitudes and phases for each harmonic content over all iterations is exhibited in Fig. 5 in non-noisy situation.

Moreover, the Gaussian noise is inoculated into the power signal at various levels of SNRs (20, 10 and 0 dB). For better and to avoid pre-mature convergence, AGSA-LS is run for 400 iterations with 50 planets moving in space in the presence of noise 20 and 10 dB SNRs. Fig. 6(b & c) expresses the performance evaluation in the existence of Gaussian noise 20 and 10 dB SNR respectively. The highest level of noise 0 dB SNR is introduced to the power signal in Gaussian form. The problem is run for 2000 iterations while 50 planets are participating in optimizing the harmonics as shown in Fig. 6(d). The estimated signals are superimposed with actual signals as clear from Fig. 7 when Gaussian noise is introduced.

Table 2 shows the comparative assessment in terms of *PER* when power signal is distorted with different levels of uniform as well as Gaussian noise. The proposed AGSA-LS confirms the better and improved results rather than GA and PSOPC. The statistical results are listed in comparison with other practices presented in the literature. The tabulated results confirm the strength and superiority of the proposed AGSA-LS in terms of lesser *PER* and computation time.

### *5.2 Harmonic Analysis of Current Drawn by a Real Time LED Lamp*

Recently, LED lamps are gaining immense attention as light source alterative of incandescent lamps and fluorescent lights because of energy saving capability. LED lamps operate on 12 V DC and are connected with power electronic based circuitry to behave as non-linear device in modern power system. The LED lamps draw non-linear current from the main source and thus distort the voltage waveform of the whole system by inoculating the harmonics. In this case study, a LED lamp was connected with source and current drawn by LED lamp was recorded with the help of digital oscilloscope. The current drawn by LED lamp is taken as power signal for harmonics estimation. The signal is saved from oscilloscope as 250 samples per cycle. The current signal drawn by LED lamp is estimated for first 8 odd harmonics i.e. 1st, 2nd, 3rd, …… 15th. The AGSA-LS is executed for 200 iterations considering 50 planets in the space for estimation of harmonics1.

Fig. 8 displays the evaluation parameters over iterations and estimated signal. From Fig. 8(b), it is apparent that actual signal is degraded due to noise at positive and negative peaks. That’s why the estimation performance parameters are larger than usual. To remove the noise, the actual signal is down sampled by factor M and then up sampled by the same factor.

The decimation basically discards the samples of the signal at regular interval including noisy samples [36]. The interpolation regenerates the discarded samples as a result of decimation [37]. The up sampled signal has having relatively lesser number of noisy samples than actual signal.

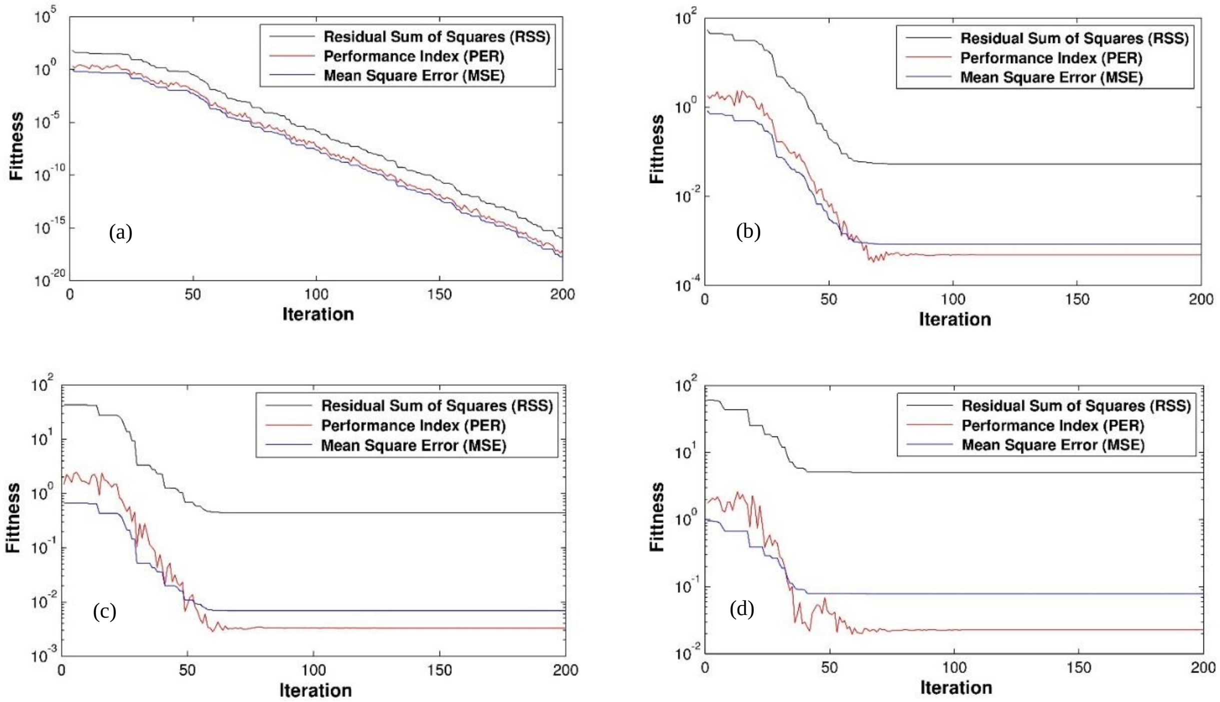


Fig. 3: Convergence characteristics of AGSA-LS while estimating harmonicsin the presence of uniform noise: (a) No noise, (b) 20 dB SNR, (c) 10 dB SNR, (d) 0 dB SNR

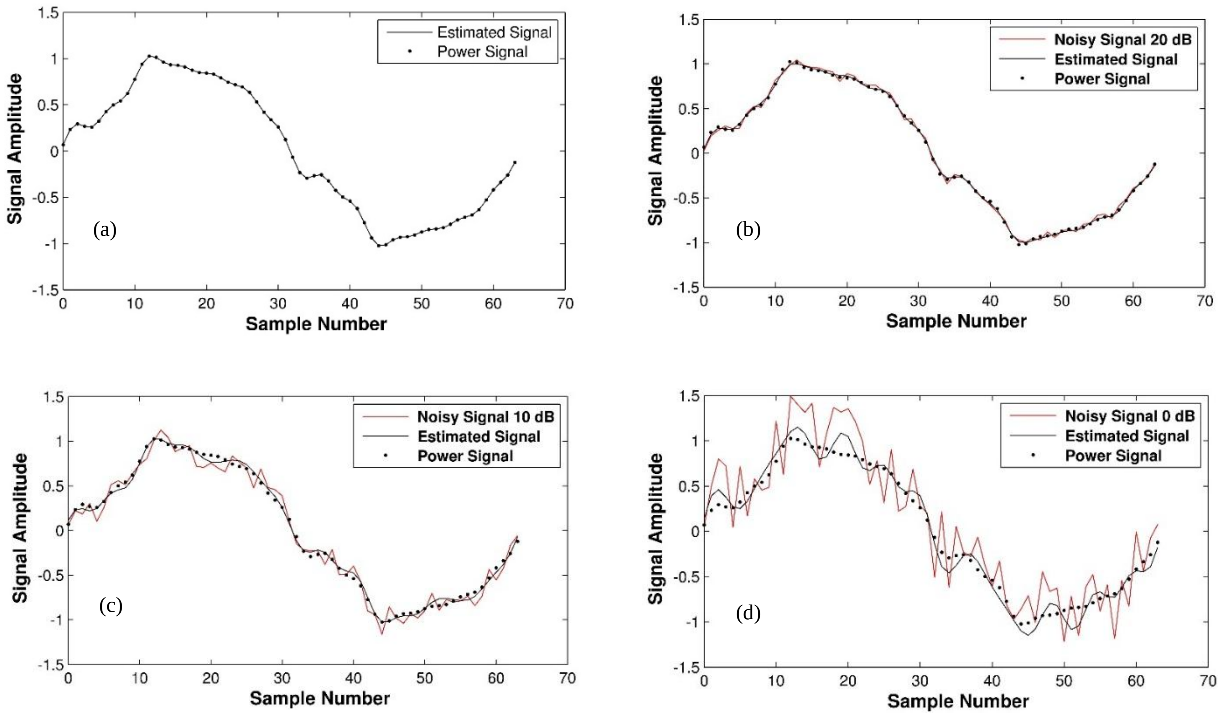


Fig. 4: Comparison of estimated and power signals in the presence of uniform noise: (a) No noise, (b) 20 dB SNR, (c) 10 dB SNR, (d) 0 dB SNR

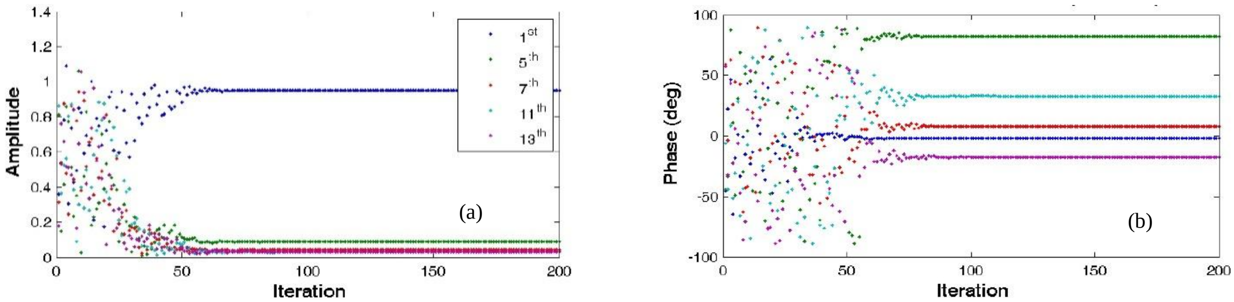


Fig. 5: Convergence characteristics while estimating individual (a) amplitudes of harmonics, (b) phases of harmonics

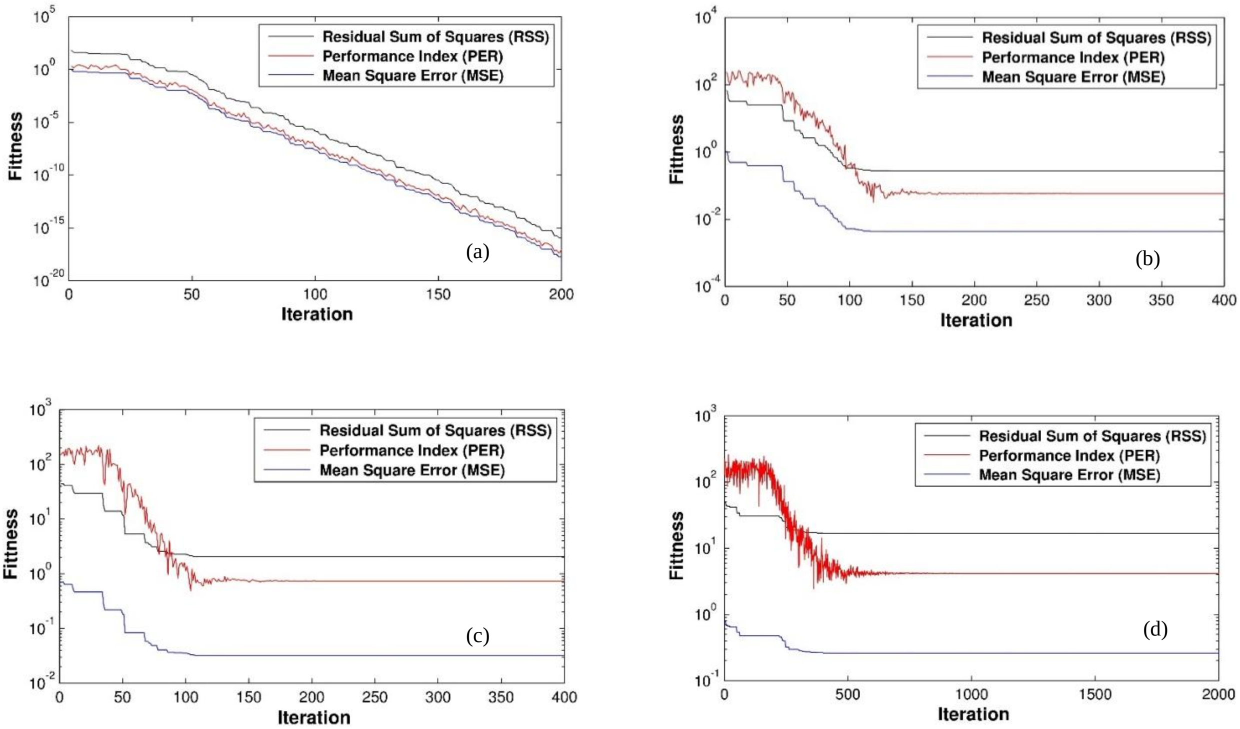


Fig. 6: Convergence characteristics of AGSA-LS while estimating harmonics in the presence of Gaussian noise: (a) No noise, (b) 20 dB SNR, (c) 10 dB SNR, (d) 0 dB SNR

The proposed AGSA-LS is applied and run on up sampled signals to estimate the harmonics and performance of this technique is judged with the help of varying sampling factor. Figs. 9-11 show the convergence of performance parameters and estimated signals when actual signal is down and up sampled by factors: 2, 5 and 7, respectively.

The statistical results are indicated in Table 3 which represent that down-and-up sampling by factor 5 and 7 are important where performance evaluation parameters are minimum. It is also evident from the Fig. 10(b) and 10(c), that down-and-up sampling by factor 5 is most suitable as compared to factor 7, and there is larger possibility of loss of information in the actual signal. The proposed AGSA-LS takes 1.454 sec for computation of harmonic contents for the case study. The 50 number of planets are contributing in optimizing the harmonic estimation for maximal 200 iterations.

The current drawn by LED lamp is the signal which exhibits the noise at positive and negative peaks as discussed earlier. To remove this type of noise, Moving Average Filter (MAF) may also be employed for smoothing the actual signal. MAF is basically the low pass filter which suppresses the drastic, tremendous and high frequency fluctuations present in the signal. This case is further analyzed to estimate the harmonics in the signal when actual signal is passed through MAF.

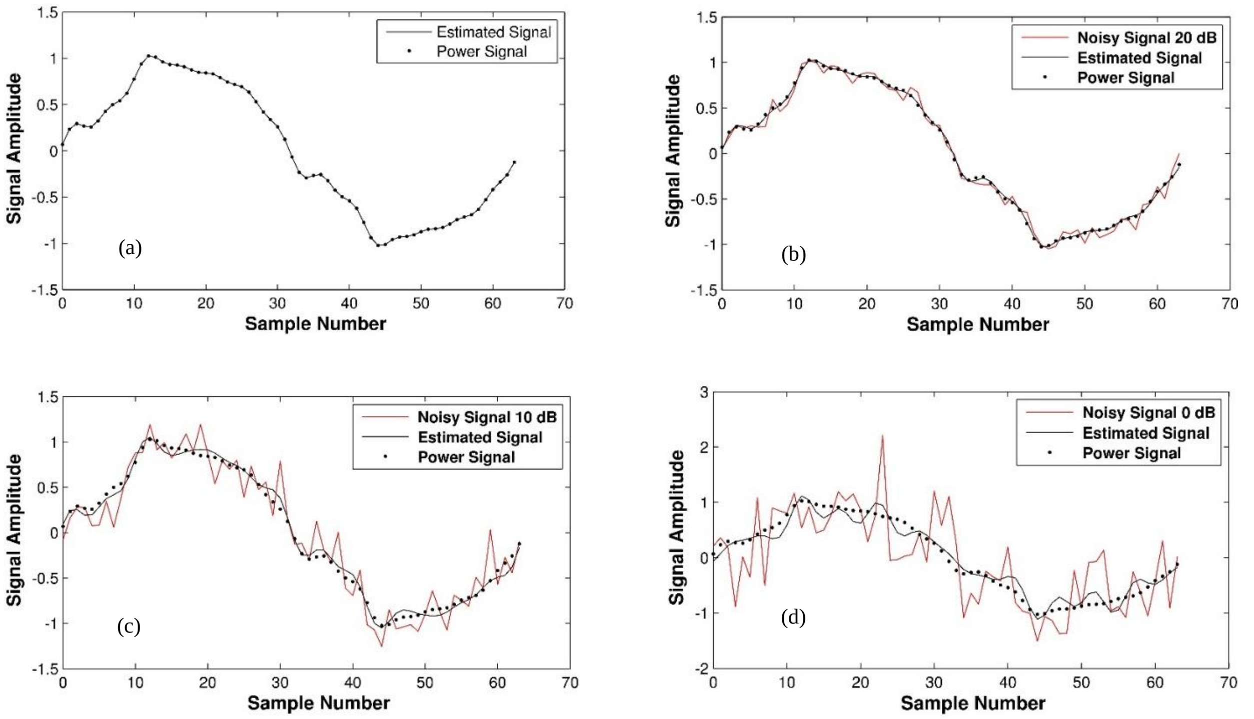


Fig. 7: Comparison of estimated and power signals in the presence of Gaussian noise: (a) No noise, (b) 20 dB SNR, (c) 10 dB SNR, (d) 0 dB SNR

Table 2: Relative performance exhibited by different practices for integral harmonics estimation

| Algorithm | Noise type | Noise level (SNR) | *PER* | *RSS* | *MSE* | Computation time (s) |
|---|---|---|---|---|---|---|
| GA [9] | Uniform | No noise | 0.0570 | – | – | 4.3492 |
| | | 20 dB | 0.1706 | – | – | |
| | | 10 dB | 0.2068 | – | – | |
| | | 0 dB | 0.5206 | – | – | |
| | Gaussian | No noise | 0.0570 | – | – | |
| | | 20 dB | 0.3995 | – | – | |
| | | 10 dB | 2.3962 | – | – | |
| | | 0 dB | 2.8913 | – | – | |
| PSOPC [23] | Uniform | No noise | $1.28\times10^{-17}$ | – | – | 3.4864 |
| | | 20 dB | 0.0045 | – | – | |
| | | 10 dB | 0.0263 | – | – | |
| | | 0 dB | 0.4550 | – | – | |
| | Gaussian | No noise | $1.28\times10^{-17}$ | – | – | |
| | | 20 dB | 0.0504 | – | – | |
| | | 10 dB | 1.1319 | – | – | |
| | | 0 dB | 2.6316 | – | – | |
| AGSA-LS | Uniform | No noise | $4.01\times10^{-18}$ | $1.17\times10^{-16}$ | $1.84\times10^{-18}$ | 1.220291 |
| | | 20 dB | 0.0003 | 0.053 | 0.0008 | |
| | | 10 dB | 0.0028 | 0.4381 | 0.0068 | |
| | | 0 dB | 0.0194 | 5.0020 | 0.0782 | |
| | Gaussian | No noise | $4.01\times10^{-18}$ | $1.17\times10^{-16}$ | $1.84\times10^{-18}$ | 2.425709 |
| | | 20 dB | 0.0321 | 0.2751 | 0.0043 | |
| | | 10 dB | 0.490 | 2.0729 | 0.0324 | |
| | | 0 dB | 2.4382 | 16.7694 | 0.2620 | |

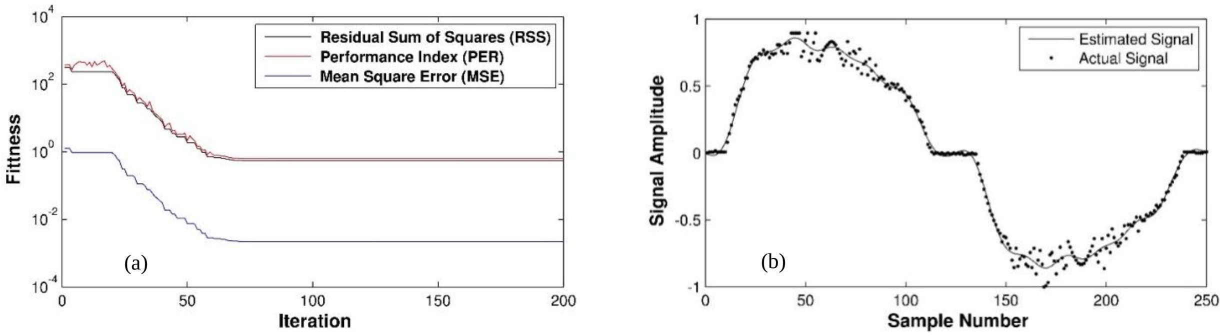


Fig. 8a: Convergence characteristics of AGSA-LS while estimating harmonics in current waveform of LED lamp, (b) Comparison of estimated and actual current signal

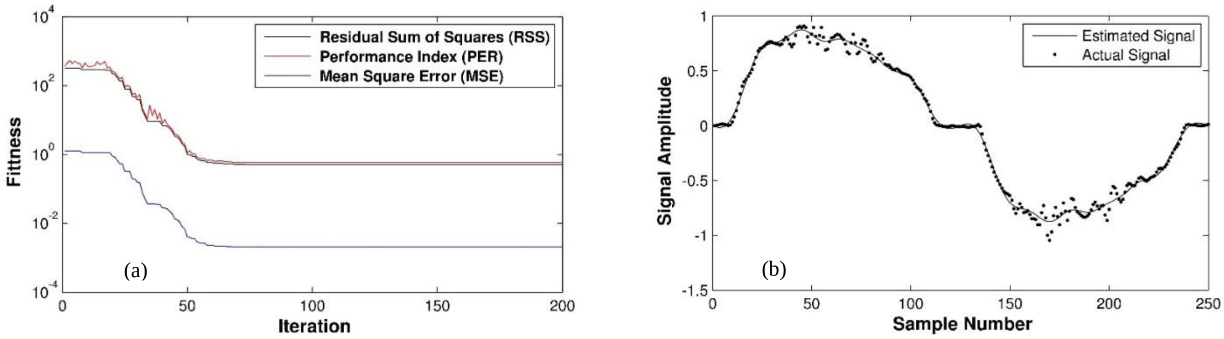


Fig. 9: At Sampling factor 2: (a) Convergence characteristics of AGSA-LS while estimating harmonics in current waveform of LED lamp, (b) Comparison of estimated and actual current signal

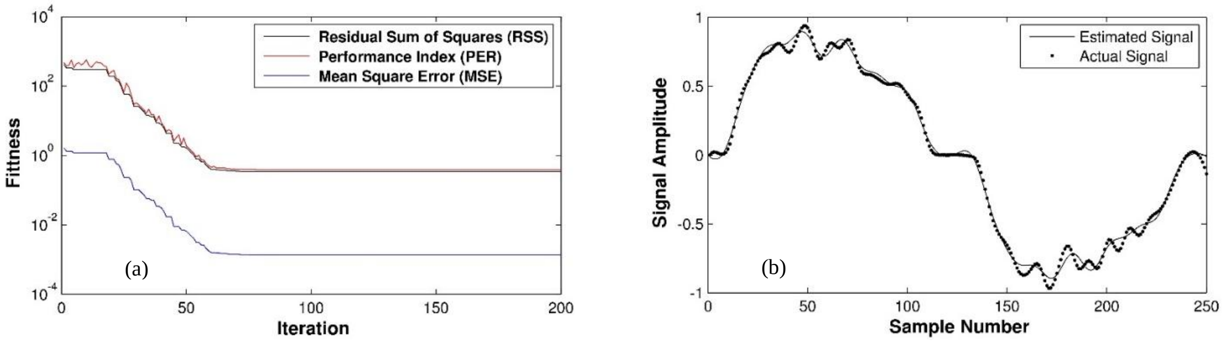


Fig. 10: At Sampling factor 5: (a) Convergence characteristics of AGSA-LS while estimating harmonics in current waveform of LED lamp, (b) Comparison of estimated and actual current signal

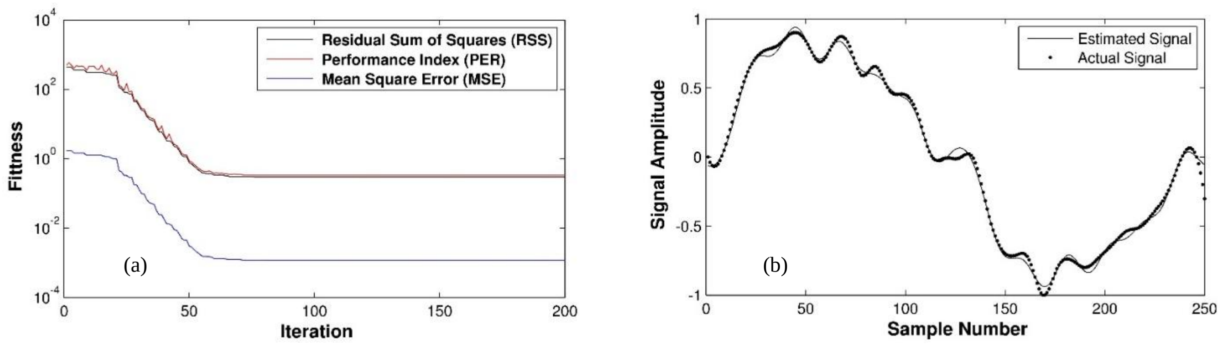


Fig.11: At Sampling factor 7: (a) Convergence characteristics of AGSA-LS while estimating harmonics in current waveform of LED lamp, (b) Comparison of estimated and actual current signal

Table 3: Effect of sampling factor on harmonics estimation in terms of performance evaluation parameters

| Sampling factor | *RSS* | *PER* | *MSE* |
|---|---|---|---|
| Actual | 0.55236 | 0.63908 | 0.0022095 |
| 2 | 0.51483 | 0.59016 | 0.0020593 |
| 3 | 0.48509 | 0.54889 | 0.0019404 |
| 4 | 0.35748 | 0.42344 | 0.0014299 |
| 5 | 0.33866 | 0.38560 | 0.0013546 |
| 6 | 0.45383 | 0.50373 | 0.0018153 |
| 7 | 0.29729 | 0.33595 | 0.0011891 |
| 8 | 0.37551 | 0.45637 | 0.0015020 |

The span of MAF is varied from 1–29 points and harmonics estimation is carried out using AGSA-LS. The results against span of MAF are shown in Fig. 12(a). From the graph, it is evident that value of RSS is minimum at 17-point MAF shown by red circle on the graph. Fig. 12(b) shows the filtered signal using 17-point MAF (Actual signal) and estimated signal. It is obvious from the graph that abrupt changes become smooth after the signal has been passed through MAF and estimation shows promising results. Simulation for harmonics estimation using MAF has been performed for maximum of 1000 iterations when 50 planets are optimizing the problem and took 6.7214 sec time. Fig. 12(c) represents the convergence of performance evaluation parameters and it is clear from the results that proposed AGSA-LS has estimated signal up to 400 iterations. The comparison for magnitudes of harmonics estimated in actual signal and signal passed thorough MAF is shown in Fig. 12(d).

## 6. Conclusion

Maiden hybridization of heuristic AGSA and LS has been proposed for effective estimation of both phases and amplitudes from noisy power signals. Results are validated both in term of accuracy (*RSS*, *MSE*, *PER*) and computational time being taken. Different theoretical and real time case studies are explored to evaluate the performance of proposed approach. For the case study, integer harmonics are extracted from power signal at different uniform as well as Gaussian noise levels (20 dB, 10 dB, 0 dB). Results clearly signifies the robustness of AGSA-LS in harmonic estimation when compared to GA and PSOPC-LS. The application of AGSA-LS has been further extended to real time current waveform by LED lamp. This diversity in usage of proposed AGSA-LS exhibits the versatility of algorithm in solving nonlinear and complex harmonic estimation problems.

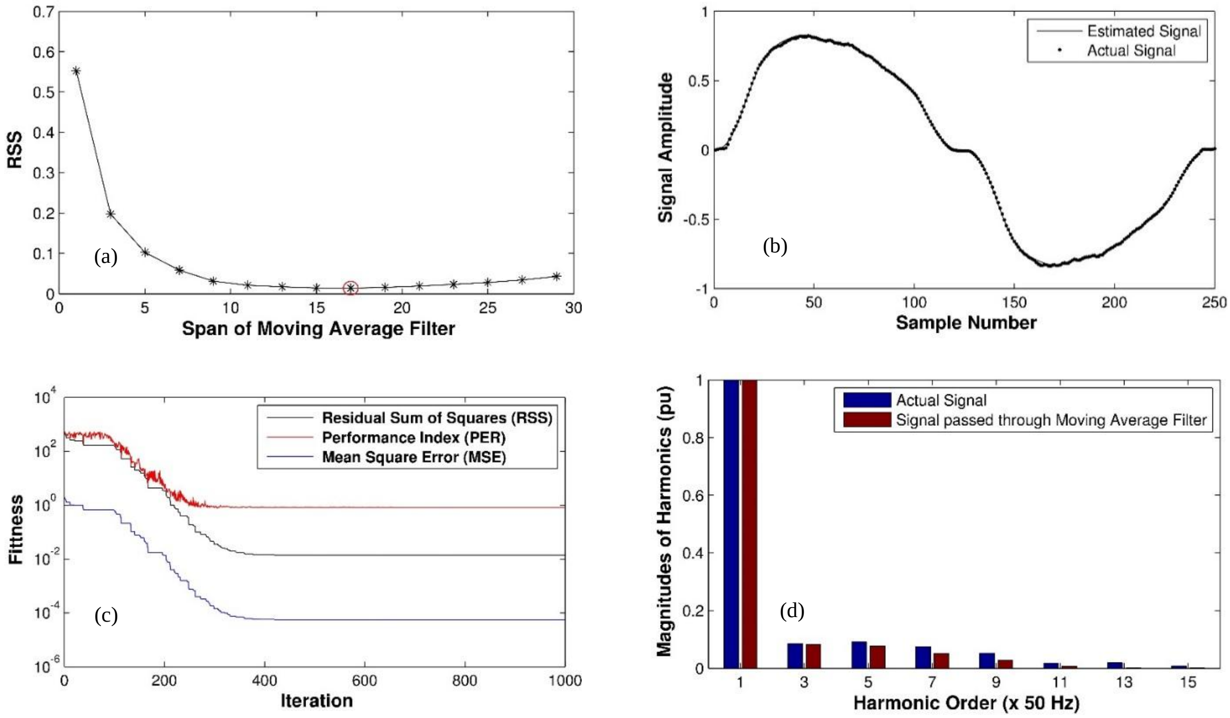


Fig. 12: (a) Effect of span MAF on RSS, (b) Comparison of estimated and actual signal, (c) Convergence characteristics of AGSA-LS while estimating harmonics, (d) Comparison for magnitudes of harmonics estimated

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