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Power System Harmonics Estimation Using Differential Evolution

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Abstract: Harmonics estimation is crucial in improving power quality. Effective mitigation of harmonics requires accurate estimation. There have been many research works that find intelligent solutions for minimizing the error index in harmonics estimation, thereby improving the accuracy. This study proposes a hybrid algorithm based on Differential Evolution (DE) and Least-Square (LS) method in which DE estimates the phases of the harmonics and LS estimates the amplitudes. Simulation results from MATLAB are presented to demonstrate that the estimation accuracy is greatly improved with the proposed algorithm when compared to evolutionary algorithms including Genetic Algorithm (GA), Particle Swarm Optimizer (PSO) and Bacterial Foraging Technique (BFT). The results confirm the capability of the proposed method in estimating power system integral harmonics and inter harmonics, even with the deviation of fundamental frequency. In addition to the simulation results, real time signals are acquired through an experimental setup using LABVIEW software and the algorithm is validated for practical signals. Results show that the method is effective with very low error index. Although, the selected area of application is power systems, the same algorithm can also be applied to other type of signals from communication channels, telephones and other encrypted signals.

Key words: Harmonic estimation, interharmonics, Differential Evolution (DE), Genetic Algorithm (GA), Particle Swarm Optimizer (PSO), Bacterial Foraging Technique (BFT).

INTRODUCTION

Harmonics is a sinusoidal component of a periodic waveform or quantity having frequency that is integral multiple of the fundamental frequency. The harmful effects of harmonics are well established in existing literature (Barnes, 1989; Arrillaga *et al*., 1985; Owen, 1998). As harmonics have much adverse effects on the equipment, IEC and IEEE has developed a standard below which harmonics should be maintained. Hence at every Point of Common Coupling (PCC), it is necessary to analyze the nature of the load that acts as a source of harmonics. A proper control strategy must be provided to mitigate the harmonics. To obtain suitable control parameter, the harmonics present in the system is to be estimated accurately.

Active and passive power filters are used to mitigate harmonics problem. Harmonics estimation is important for their proper design. Similarly for all control designs, accurate assessment of harmonics is considered as important. A distorted signal is composed of a fundamental frequency along with n harmonics buried in stochastic noise. There is a need of estimating the desired frequency components in the signal to filter harmonics. This estimation includes estimating the amplitude and phase of the corresponding frequency component. Estimation algorithms have been developed to obtain certain parameters from the signal to enhance the harmonics measurement in the system.

The different approaches to estimate the harmonics include Discrete Fourier Transform (DFT) (Zhu, 2007), Kalman filtering (Costa *et al*., 2007), decoupled models (Lobos *et al*., 2001) and artificial neural networks (Kumar *et al*., 2007). Though DFT-based methods are commonly used, there are snags such as aliasing, leakage and picket fence phenomena in their applications under undesirable conditions. Kalman filtering methods are linear and robust but need knowledge of the statistics of the electrical signal and precise definition of the signal states. Decoupled methods are identified to possess slow roll off speed (Ray and Subudhi, 2012).

The literature review has identified harmonics estimation as a minimization problem involving non-linear model in which the error between the actual and estimated value is to be minimized. Hence, the problem can be handled using optimization techniques. Genetic algorithm techniques have been found to give superior results for optimization problem in harmonics estimation (Bettayeb, 1998) but it requires a larger time for convergence with monotonic nonlinear models.

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To overcome these disadvantages, a hybrid technique has been proposed combining GA and LS . In this technique, phases are estimated using GA and amplitudes are estimated with LS. It has been found that the efficiency of GA reduces significantly degraded when it is applied to a function where the parameters that are optimized are highly correlated (Mishra, 2005). Hybrid PSO-LS technique is proposed in (Lu *et al*., 2008) for harmonics estimation. PSO shares many similarities with evolutionary computation techniques such as Genetic Algorithms (GA) (Yang *et al*., 2005). The system is initialized with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles (Miranda and Fonseca, 2002; Eberhart and Shi, 2001; He *et al*., 2004). Bacterial foraging technique is used in (Kumar *et al*., 2006). BFO follows the principle of the foraging behavior of Escherichia coli bacteria in human intestine (Passino, 2002; Kim *et al*., 2007).

Differential evolution is a very simple but very powerful stochastic optimizer. Since, its inception, it has proved very efficient and robust in function optimization and has been applied to solve problems in many scientific and engineering fields (Qin *et al*., 2009). In this study, hybrid differential evolution-least square method is proposed. The DE is applied to optimize the phase of each individual harmonic and least square technique is used to obtain the magnitude of each harmonics in a signal.

Power system harmonic estimation problem: In this study, the modeling of power system harmonics estimation problem is presented. The harmonic parameters, the amplitude and the phase angle are estimated using the nonlinear DE optimization algorithm and the linear LS method. Let the assumed electrical signal structure at time t be:

$$f(t) = \sum_{n=1}^{N} A_n \operatorname{Sin}(\omega_n t + \varphi_n) + v(t) \qquad (1)$$

Where:

- N = No. of harmonics
- A_n = Amplitude of nth harmonic
- ω_n = Angular frequency of nth harmonic
- φ_n = Phase angle of nth harmonic
- V(t) = Additive noise

To estimate the unknown parameters of each harmonic, the following function is built:

$$g(t) = \sum_{n=1}^{N} B_k \operatorname{Sin}(\omega_n t + \theta_n) \qquad (2)$$

The built signal g(t) is related to the original signal f(t) by the Eq. 3:

$$f(t) = g(t) + r(t) \qquad (3)$$

Where, r(t) is a residue indicating the difference between actual and built signals. If r(t) tends to 0 then the estimated parameters exactly equals magnitudes and phases of the original signal. Hence, the task is to force r(t) to a minimum value.

The basic known fact is that the values of phases fall in the range 0-2π. The differential evolution algorithm is utilized to obtain the values of phases and once, the phases and the frequencies are implicit in each iteration, the amplitude is obtained by the standard Least square regression method.

Discrete model for the continuous system given in Eq. 1 is developed with "S" number of samples. Equation 4 represents the function model with S samples:

$$f(k) = H'(k)A + V(k);\ k = 1,2,\ldots S \qquad (4)$$

Where: H'(k) is a system structure matrix and given by 5:

$$H'(k) = \begin{bmatrix} \sin(w_1 t_1 + \varphi_1) & \sin(w_2 t_1 + \varphi_2) & \ldots & \sin(w_n t_1 + \varphi_n) \\ \sin(w_1 t_2 + \varphi_1) & \sin(w_2 t_2 + \varphi_2) & \ldots & \sin(w_n t_2 + \varphi_n) \\ \ldots & \ldots & \ldots & \ldots \\ \sin(w_1 t_S + \varphi_1) & \sin(w_2 t_S + \varphi_2) & \ldots & \sin(w_n t_S + \varphi_n) \end{bmatrix} \qquad (5)$$

Where, A is a column matrix of amplitude of original signal. Primarily, an optimization algorithm optimizes the values of phases of fundamental and harmonics signals and the system structure matrix H(k) given by Eq. 7 is computed. Once, the system structure matrix is obtained, the magnitude estimation is done by applying the least square method given by Eq. 6:

$$B = \left[H^t(k)H(k)\right]^{-1} H^t(k)f(k) \qquad (6)$$

Where H (k) is given by:

$$H(k)=\begin{bmatrix} \sin(w_1t_1+\theta_1) & \sin(w_2t_1+\theta_2) & ..... & \sin(w_nt_1+\theta_n) \\ \sin(w_1t_2+\theta_1) & \sin(w_2t_2+\theta_2) & ..... & \sin(w_nt_2+\theta_n) \\ ..... & ..... & ..... & ..... \\ \sin(w_1t_s+\theta_1) & \sin(w_2t_s+\theta_2) & ..... & \sin(w_nt_s+\theta_n) \end{bmatrix} \quad (7)$$

B is the matrix of estimated amplitudes of the signal. If the values of $\theta=\varphi$ then the estimated phases matches with the actual phases. The estimated signal will be given by Eq. 8:

$$g(k)=H(k)B \quad (8)$$

The residue at each sample is the difference of magnitudes of the signal at that instant and the total residue is calculated using Eq. 9:

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

The algorithm optimization repeats until the total residue falls below specific tolerance limit. After the convergence of the problem, the fundamental component present in the signal is computed by:

$$\text{fund}(t)=A_1\,\text{Sin}(\omega_1 t+\varphi_1) \quad (10)$$

The harmonic components are obtained by:

$$\text{har}(t)=g(t)-\text{fund}(t) \quad (11)$$

MATERIALS AND METHODS

Differential Evolution (DE): Differential evolution was formulated by Ken price to solve the Chebychev Polynomial fitting problem effectively. The DE uses vector differences for perturbing the vector population. The DE leads to good exploration, since random direction is generated by simple vector subtraction and more variation in population leads to more search over solution space. The following is the description of DE algorithm used in this research.

Algorithmic description of DE: The main steps of the DE algorithm are given below:

Initialization
Evaluation
Repeat:
Mutation
Recombination
Evaluation
Selection
Until (termination criteria are met)

Differential evolution can be briefly explained as follows:

Initialization: Differential evolution is a population based optimization method. In the population of Np individuals $X_{i,g}$ is the ith individual of gth generation of the population. The first population is selected randomly in differential evolution.

The mutation: There are several techniques for mutation of individuals in differential evolution. In general, the mutant individual can be defined as follows:

$$V_{i,g}=X_{i,g}+F\frac{1}{N}\sum_{n=0}^{N-1}(x)_{r(2n+1)},g-(x)_{r(2n+2)},g \quad (12)$$

Where, $V_{i,g}$ is the mutant vector, $X_{i,g}$ is the base vector and F is a constant parameter called mutation scale factor. N represents the number of vector differences considered for the formation of mutant vector. The subscript r shows that the individual is selected randomly in the population.

The crossover: The most common crossover in differential evolution is uniform crossover which can be defined as follows:

$$U_{i,g}=\begin{cases} V_{j,i,g}, \text{if } r_j\le C_r \\ X_{j,i,g}, \text{if } r_j\le C_r \end{cases} \quad (13)$$

Where:

r_j = A uniformly distributed random number and subscript
j = The variable of the ith individual
C_r = A constant parameter called crossover constant

The selection: The final step in DE algorithm is the selection of the better individual for the minimization of the objective function f(X). This process can be defined as follows:

$$X_{i,g+1}=\begin{cases} U_{i,g}, \text{if } f(U_{i,g})\le f(X_{i,g}) \\ X_{i,g}, \text{if } f(U_{i,g}) \rangle f(X_{i,g}) \end{cases} \quad (14)$$

The selection process involves a simple replacement of the original individual with the obtained new individual if it has a better fitness. Number of vector differences is usually taken as 1. There are three control parameters in the DE algorithm: the mutation scale factor

Estimation of phase and amplitude of integral harmonics: The phases and amplitudes of integral harmonics are estimated using the following procedure. Inputs required for the estimation of harmonics are the number of harmonics to be estimated, number of samples (S), sampled time and the corresponding magnitude of the signal at the sampled time. The proposed algorithm is described as follows:

Step 1: Initialize the number of harmonics to be estimated, parameters of differential evolution such as number of population, mutation scale factor and crossover constant.

Step 2: Load the data set that comprises of the sampled time and the magnitude of distorted voltage/current signal.

Step 3: Generate the initial population randomly within the limits of the variables. Hence, 'Np' number of solutions are created as $X_i = [\theta_{1i}, \theta_{2i}, ..., \theta_{ni}]$. I = 1, 2, ..., np.

Step 4: For each individual solution, H(k) is calculated using Eq. 7. By using H(k) matrix, B and subsequently g(k) are computed using Eq. 6 and 8 respectively. Residue R is calculated using Eq. 9. The objective function to be minimized is:

$$\text{Minimize} = R \tag{15}$$

Step 5: The differential evolution operators such as mutation, crossover and selection is repeated for all the individuals of the population using Eq. 12-14 and a new population is created for the next generation.

Step 6: The steps 4 and 5 are repeated until the convergence criteria is met.

Objective function R is checked for the error tolerance. If it is less than the tolerance value then the fitness value is considered as the best solution. If not, the algorithm moves to next generation. Thus, the production of offspring for the next generation consists of mutation, crossover and selection step in sequence. The algorithm terminates if convergence occurs or the number of generations reaches its maximum value. The flowchart for the proposed algorithm is given in Fig. 1.

Estimation of frequency: Harmonic frequencies are the integer multiples of the fundamental frequency, the frequency for each harmonic can be calculated only if the fundamental frequency is known. Hence, harmonic estimation requires the estimation of the fundamental frequency. In real time power systems, frequency deviation widely exists. For the estimation of frequency

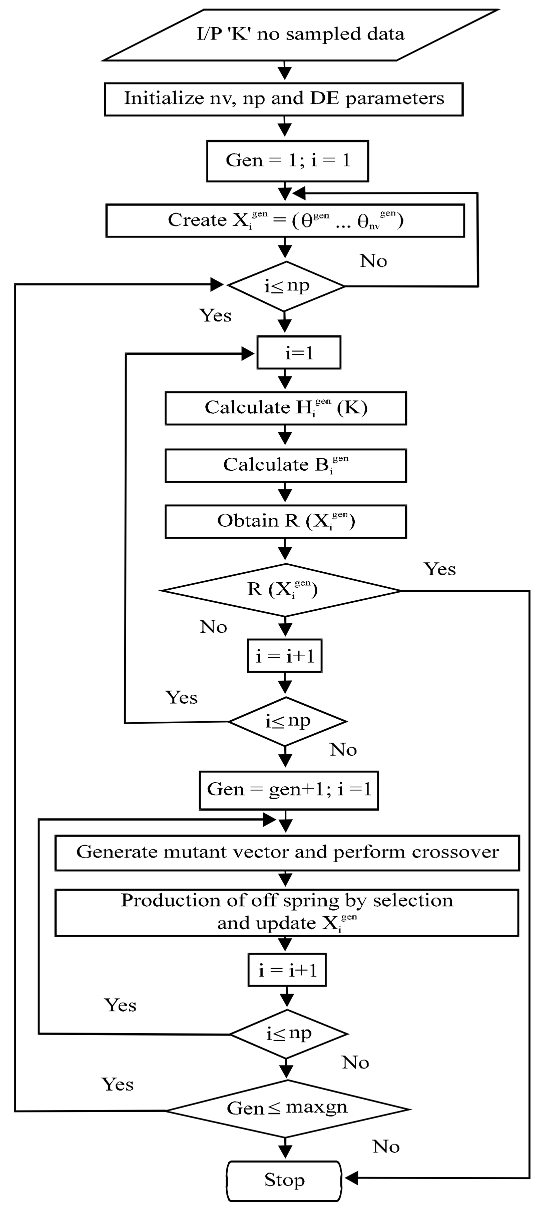

Fig. 1: Flow chart of the proposed algorithm

along with the estimation of integral harmonics, the solution set $x = [\theta_1, \theta 2, ... \theta_n]$ is modified to $x = [\theta_1, \theta 2, ... \theta_n, w_0]$ where, w_0 is the variable denoting the fundamental frequency. Thus, the number of variables is increased by one. The system structure is modified as follows:

$$H(k) = \begin{bmatrix} \sin(w_0 t_1 + \theta_1) & \sin(2w_0 t_1 + \theta_2) & ..... & \sin(nw_0 t_1 + \theta_n) \\ \sin(w_0 t_2 + \theta_1) & \sin(2w_0 t_2 + \theta_2) & ..... & \sin(nw_0 t_2 + \theta_n) \\ ..... & ..... & ..... & ..... \\ \sin(w_0 t_S + \theta_1) & \sin(2w_0 t_S + \theta_2) & ..... & \sin(nw_0 t_S + \theta_n) \end{bmatrix} \tag{16}$$

Thus, in this case, all the elements in the matrix H(k) depends on two independent variables w_0, the fundamental frequency and θ, the phase angle.

Estimation of interharmonics: International Electrotechnical Commission (IEC), the international body which is recognized as the curator of electric power quality standards (IEC-1000-2-1) officially defined interharmonics as 'Between the harmonics of the power frequency voltage and current, further frequencies can be observed which are not an integer of the fundamental. They can appear as discrete frequencies or as a wide-band spectrum'. A recent IEC-61000-2-2 draft redefines interharmonic as 'Any frequency which is not an integer multiple of the fundamental frequency'. IEEE Interharmonic Task Force adopted this definition. In some cases, it becomes necessary to estimate interharmonics along with the harmonics. To obtain interharmonics component, an additional column in H(k) matrix is introduced with unknown interharmonics frequency. A prior knowledge is required to fix the boundary for this additional variable. For the estimation of interharmonics and subharmonics, the solution set $X = [\theta_1, \theta_2, \ldots \theta_n]$ is modified to $X = [\theta_i, \theta_1, \theta_2, \ldots \theta_n, \omega_i]$. Thus, the number of variables is increased by two including the frequency of the interharmonics and the phase angle of that particular component. The system structure is modified as follows:

$$H(k) = \begin{bmatrix} \sin(w_1 t_1 + \theta_1) & \sin(w_2 t_1 + \theta_2) & \ldots\ldots & \sin(w_n t_1 + \theta_n) & \sin(w_i t_1 + \theta_i) \\ \sin(w_1 t_2 + \theta_1) & \sin(w_2 t_2 + \theta_2) & \ldots\ldots & \sin(w_n t_2 + \theta_n) & \sin(w_i t_2 + \theta_i) \\ \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots \\ \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots \\ \sin(w_1 t_s + \theta_1) & \sin(w_2 t_s + \theta_2) & \ldots\ldots & \sin(w_n t_s + \theta_n) & \sin(w_i t_n + \theta_i) \end{bmatrix} \quad (17)$$

RESULTS AND DISCUSSION

The typical power system current signal in industrial UPS load is used for the simulation. The algorithms are tested with harmonic signals generated under different load conditions. The result for one of the load conditions is presented in detail.

The signal considered contains fifth, seventh, eleventh, thirteenth and fifteenth order frequency components addition to the fundamental frequency. Table 1 shows the magnitude and phase angle of the harmonics and fundamental present in the waveform simulated.

The comparison between FFT, DFT and optimization algorithms for the application of harmonics estimation are made. This study compares the hybrid techniques involving the optimization algorithms and Least Square method. To illustrate the effectiveness of the proposed algorithm, the hybrid DELS algorithm is compared with hybrid GALS (Maamar, 2003), hybrid PSOLS (Lu *et al*., 2008), hybrid BFT (Ray and Subudhi, 2012).

Table 1: Magnitude and phase angle of the harmonics and fundamental present in the waveform simulated

Harmonic order (deg)	Magnitude (pu)	Phase (rad)	Phase
1(fundamental)	1.000	-0.0353	-2.02
5	0.251	0.0500	2.86
7	0.177	0.1379	7.90
11	0.083	-2.5674	-147.10
13	0.048	0.000	0.00
15	0.001	0.054	3.09

Estimation of amplitudes and phases: Signals are sampled at the frequency of 2 kHz and the sampled points are given as the input to the estimation algorithm. Initially random phases are introduced by differential evolution and using these phase values H matrix in Eq. 7 is constructed. It is assumed that the frequency is known. The analysis is done in the following aspects.

Case (a): All the algorithms are made to run for 4 sec and at the end of the elapsed time, the best solution is taken as the result.

Case (b): All the algorithms are made to run to obtain error index <0.1

The signal is simulated along with random noises with different Signal to Noise Ratio (SNR) in either cases.

Results of Case (I): The algorithms runs are taken as 50 from which the best, worst and average values of error are computed. As the effectiveness of the algorithm is to be tested with the presence of noise, random noise of 40, 25 and 10 db is added to the original signal and the error index is obtained. Error index is obtained from Eq. 18:

$$E = \frac{\sum_{k=1}^{s}=\left(g(k)-f(k)\right)^2}{\sum_{k=1}^{s}=f(k)^2} \times 100 \quad (18)$$

From the values in Table 2, it is clear that the proposed DELS algorithm has lower error index. The figure gives the comparison between the actual signal and estimated signal for all the four algorithms considered. The reconstructed signal is almost identical to the original signal when the SNR is high. When the noisy condition gets worse, the estimating result still maintains the approximate shape. Comparison of error in the estimation of all frequencies in the signal is given in Table 2.

Figure 2 and 3 gives the comparison of original and estimated waveform without the presence of noise and

Table 2: Comparison of error in estimation of all harmonics for run = 50

	GA-LS			PSO-LS			BFT-LS			DE-LS		
Noise	Worst	Best	Average	Worst	Best	Average	Worst	Best	Average	Worst	Best	Average
No noise	0.0360	0.0008	0.0179	0.0503	0.0501	0.0501	0.0625	0.0017	0.043	0.0016	0.0003	0.0008
SNR = 40db	0.0779	0.0027	0.0029	2.5826	0.2826	0.3204	0.0598	0.0560	0.0553	0.0021	0.0010	0.0019
SNR = 25db	0.2603	0.0882	0.1071	2.6038	0.1042	0.8975	0.1399	0.1259	0.1332	0.1776	0.1025	0.1059
SNR = 10db	1.3075	0.7913	0.8572	3.4294	3.3490	2.2045	2.7492	0.7127	1.5502	1.6854	1.3684	1.3737

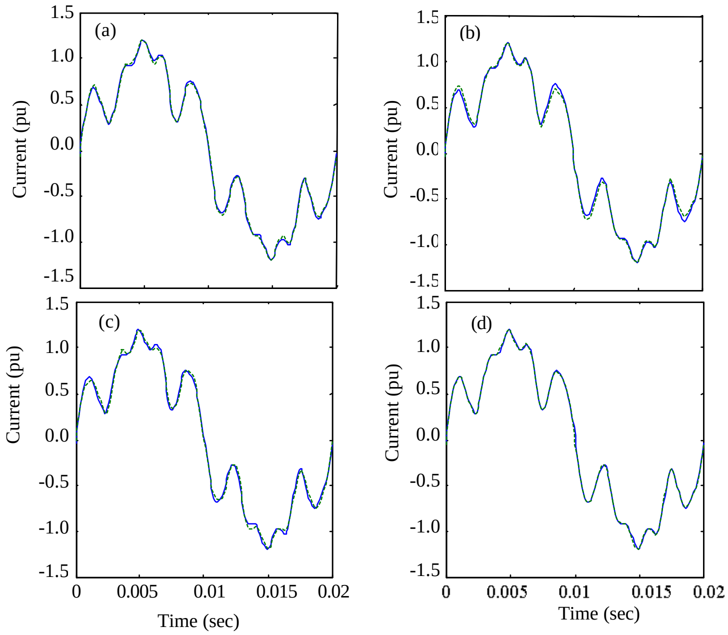

Fig. 2: Comparison of original and estimated waveforms; a) GALS; b) PSOLS; c) BFTLS and d) DELS without noise

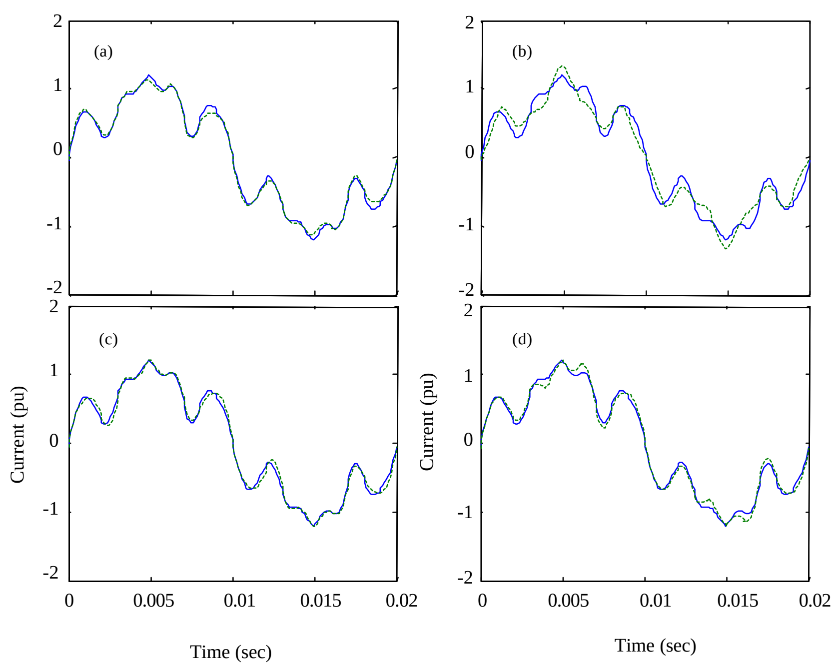

Fig. 3: Comparison of original and estimated waveforms; a) GALS; b) PSOLS; c) BFTLS and d) DELS with noise (SNR = 25db)

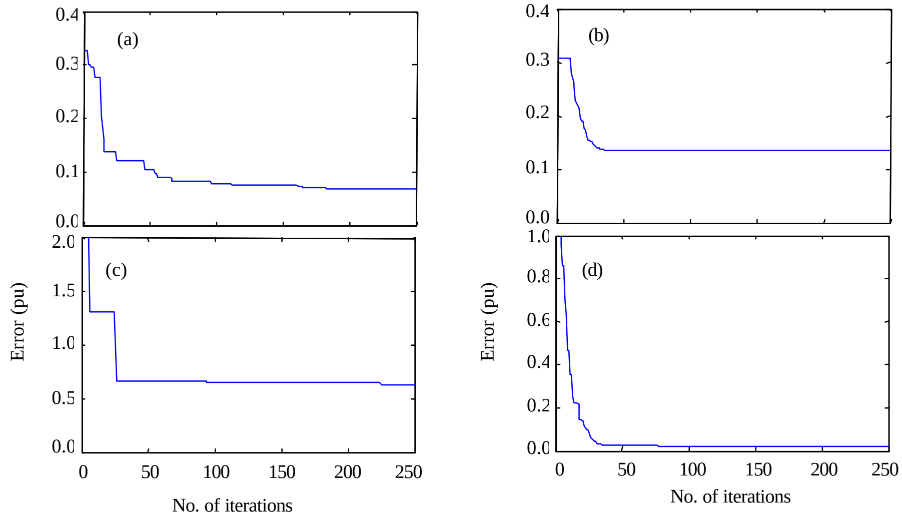

Fig. 4: Convergence for 250 generations; a) GALS; b) PSOLS; c) BFTLS and d) DELS

Table 3: Estimated magnitude values compared to the original value

Harmonic order	Magnitude (pu)	GALS	PSOLS	BFTLS	DELS
1(fundamental)	1.000	1.0001	0.9994	1.0001	1.0001
5	0.251	0.2509	0.2495	0.2509	0.2509
7	0.177	0.1765	0.1753	0.1766	0.1766
11	0.083	0.0795	0.084	0.0797	0.0837
13	0.048	0.048	0.0466	0.0479	0.0480
15	0.001	0.0011	0.0009	0.0010	0.0011

Table 4: Estimated phase angle values compared to the original value

Harmonic order	Phase (rad)	GALS	PSOLS	BFTLS	DELS
1(fundamental)	-0.0353	-0.0339	-0.0330	-0.0367	-0.0372
5	0.05	0.0552	0.0470	0.0592	0.0495
7	0.1379	0.0737	0.1395	0.0857	0.0813
11	-2.5674	3.1369	3.6940	3.1416	0.0016
13	0	-0.0150	-0.1680	-0.114	-0.0333
15	0.054	0.0576	0.0598	0.0561	0.0563

SNR = 25 db, respectively. The convergence graphs of the algorithms for 250 generations are given in Fig. 4. The error in the graph shows the absolute maximum error between the estimated and actual values of the waveform at the sampled instants.

Results of case (b): In the second case, the algorithms are set free to run until convergence takes place. The error index computed from Eq. 13 is fixed as 0.1. As the nature of evolutionary algorithms is a usage of random numbers greatly, the time for the convergence differs in each run. The average time also depends on the initial solution considered which is created random again. Hence, the total run of each algorithm is taken as 50 to obtain a proper statistical data for comparison. The average time is computed for convergence to obtain error index <0.1 for the four algorithms for 50 runs. The average time for GALS, PSOLS, BFTLS and DELS is 8.4, 7.3, 6.12 and 4.46s, respectively. Table 3 and 4 shows the estimated magnitude values compared to the original value. Table shows the estimated phase angle values compared to the original value.

Separation of fundamental and harmonics signals: The fundamental component estimation is considered primarily important to obtain the real and reactive component of the signal. The fundamental signal is determined from the Eq. 10 and the comparison of original and estimated is given in Fig. 5.

The active harmonic mitigating device which researchess on the principle of injection of harmonics required the measurement of harmonics present in the signal. The algorithm additional to the estimation of integral harmonics also segregates the fundamental and harmonics components according to the requirement. The comparison of the harmonics present in the signal with the estimated harmonics is given in Fig. 6.

Estimation of frequency: The proposed algorithm can be applied to detect the deviation of the fundamental frequency effectively. It is done by adding the unknown fundamental frequency into the variable. The number of variables is increased by 1 in this case. The range of frequency is given between 46 and 54 Hz for an electrical signal of rated frequency of 50 Hz. A huge number of UPS current waveforms are simulated with different frequencies within this range. The frequencies are varied from 46 Hz in steps of 0.005 up to 54 Hz and 1600 similar waveforms are simulated and tested. It is observed that all the algorithms determine the frequency effectively within the tolerance of 0.1 Hz. The average time taken by the algorithms increased approximately by 15%. Figure 7 shows the comparison of original and estimated signal in the frequency of 50.5 Hz.

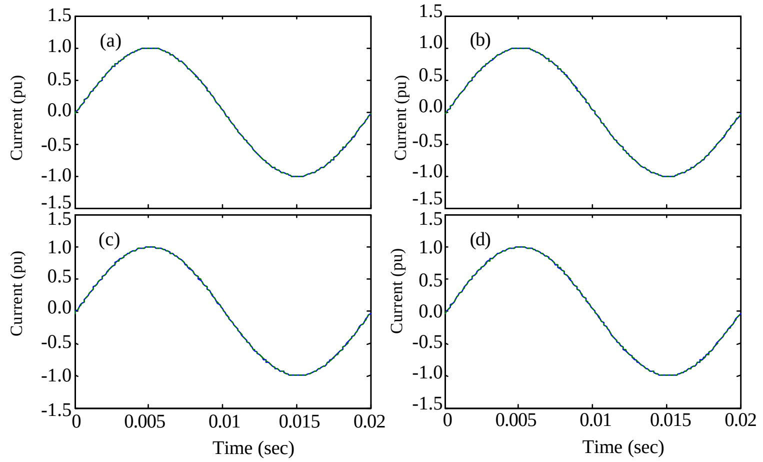

Fig. 5: Comparison of original and estimated fundamental waveform; a) GALS; b) PSOLS; c) BFTLS; d) DELS

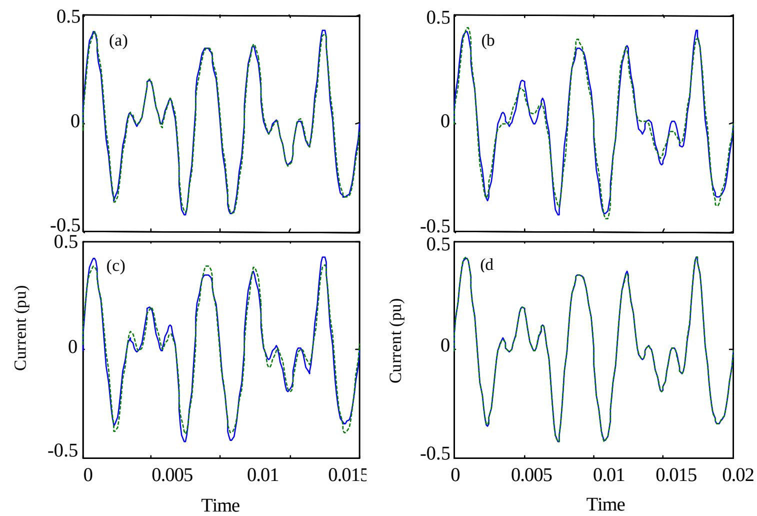

Fig. 6: Comparison of original and estimated harmonic signals; a) GALS; b) PSOLS; c) BFTLS; d) DELS

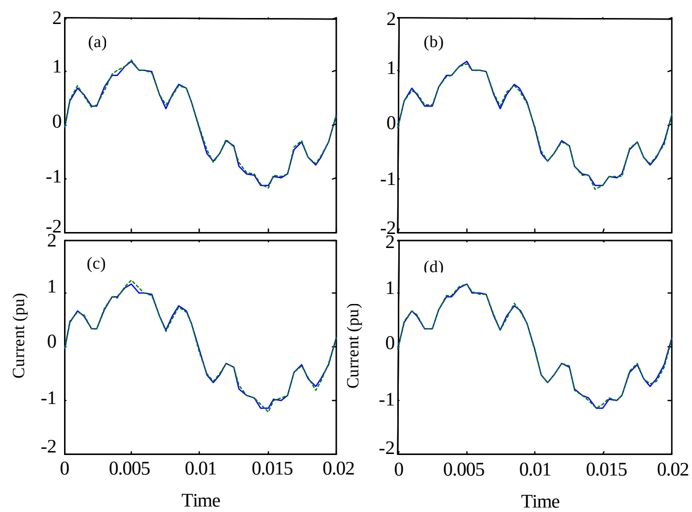

Fig. 7: Comparison of original and estimated waveforms; a) GALS; b) PSOLS; c) BFTLS; d) DELS with frequency = 50.5 Hz

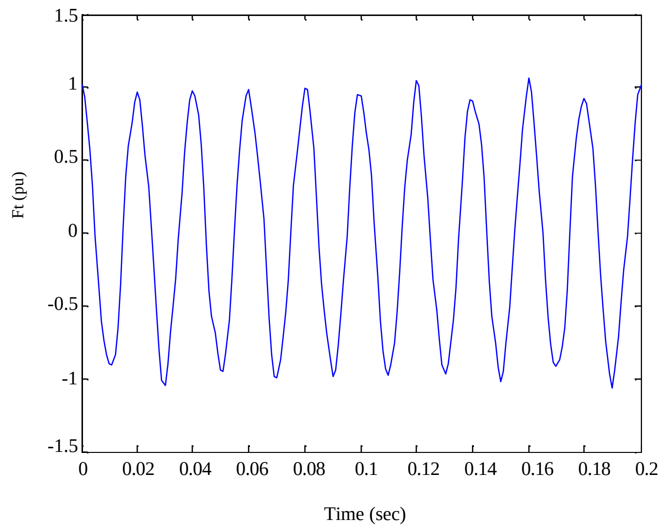

Fig. 8: Simulated signal with interharmonics

Fig. 9: Hardware setup

Measurement of interharmonics signal: The performance of the proposed algorithm is evaluated in the estimation of a signal in the presence of interharmonics. In this research to obtain interharmonics and subharmonics component, window size is suitably increased and the basic frequency ω_1 in H(k) matrix is fixed as 5 Hz. Hence, the size of H(k) matrix and the number of input cycle data is increased to obtain the sub harmonics and interharmonics present in the system. The data for 10 cycles is given as input to obtain the subharmonics and interharmonics in the range of multiples of 5. The signal simulated is Fig. 8:

$$f(t) = 0.96\cos(2\Pi 50t) + 0.05\cos(2\Pi 125t)\Pi/4 + 0.045\cos(2\Pi 180t + \Pi/2) + 0.02\cos(2\Pi 250t) \quad (19)$$

Table 5: Error computation in interharmonics estimation

GA-LS	PSO-LS	BFT-LS	DE-LS
0.0124	0.0558	0.0234	0.0101

The average error for all the four methods are obtained from the Eq. 18 and is provided in Table 5.

Experimental studies and results: For further validation of the proposed algorithm, a voltage signal is generated experimentally and the proposed method is applied to determine the harmonics in the signal. The experimental setup consists of an arc welder connected to the coil of an induction motor and is shown in Fig. 9. The voltage signal is acquired using lab view software and the connected data cord. The signal is sampled at the rate of 2 kHz and the

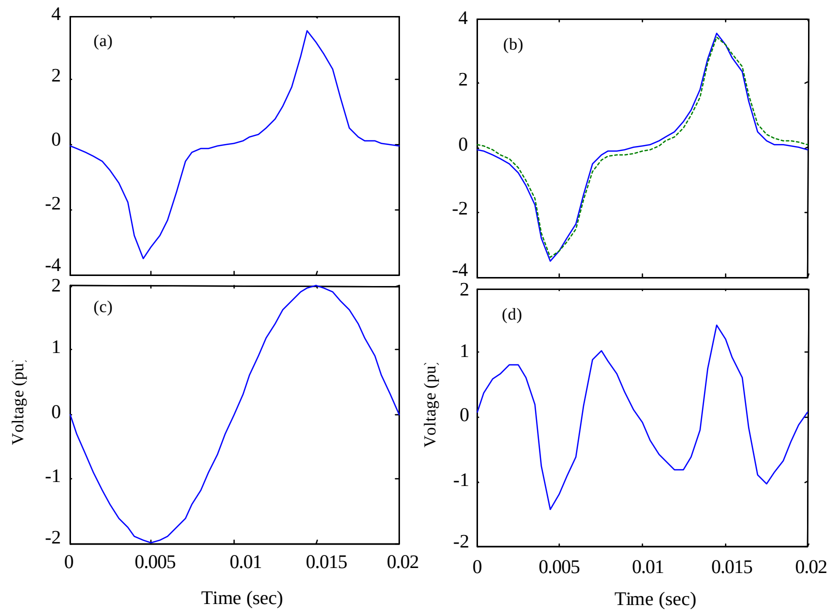

Fig. 10: a) Voltage signal from arc welder; b) original and estimated waveforms; c) fundamental component in the signal and d) harmonics component in the signal

Table 6: Error comparison for experimental data

GA-LS			PSO-LS			BFT-LS			DE-LS		
Worst	Best	Average	Worst	Best	Average	Worst	Best	Average	Worst	Best	Average
0.0067	2.00E-05	0.0012	0.0203	0.0021	0.0067	0.0009	3.00E-05	0.0051	9.00E-04	3.00E-06	1.00E-04

sampled signal is imported to MATLAB environment and tested with the algorithm. The sampled signal is validated using Digital Signal Oscilloscope. Figure 10 gives the experimentally generated waveform, the comparison of reconstructed waveform using sampled data and estimated data, the extraction of fundamental and harmonics present in the signal respectively. Table 6 gives the error comparison between the four optimization methods for the experimental data.

CONCLUSION

Power quality monitoring requires accurate estimation of amplitudes and phases of the harmonics in any electrical signal. Harmonics estimation in a power system comprises of power electronic devices using the evolutionary algorithms have been investigated in the study. This study uses an effective method based on differential evolution and least square technique for the estimation of accurate harmonic characteristics. The estimation process is fast and iterative. In each generation, the algorithm first applies DE to estimate the phases and the frequencies and then calculates the amplitudes using LS method. The corresponding frequency spectrum is obtained. The time taken for the proposed algorithm is less compared to other hybrid techniques. The simulation results demonstrate that the proposed algorithm is able to be applied for the estimation of harmonics and interharmonics, even in the case of the deviation of the fundamental frequency. The proposed algorithm convergences within few seconds and hence, the algorithm could be used for online applications.

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