Received May 6, 2021, accepted May 11, 2021, date of publication May 17, 2021, date of current version May 24, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3081037

Sine Cosine Algorithm Approaches for Directly Estimation of Power System Harmonics & Interharmonics Parameters

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ABSTRACT In order to maintain the power quality, parameters of harmonic and sub-inter-harmonic components in the signal must be estimated accurately with less computational complexity. In power systems, the value of fundamental frequency changes between 49.5Hz and 50.5Hz and this situation causes the frequency of other harmonic components to change. In order to make efficient amplitude and phase estimation, initially, frequencies must be estimated properly. In this study, the Sine Cosine Algorithm is applied for the estimation of harmonics and sub-inter-harmonics parameters in the power systems. Unlike other optimization-based methods in the literature, it is assumed that the frequencies of the harmonic and sub-inter-harmonic components in the signal are not known. The proposed algorithm has been tested on synthetic signals at different noisy environment. Given the results obtained, SCA can predict the frequencies, amplitudes, and phases of harmonics and sub-inter-harmonics with less than 5% error, which is the maximum error limit specified by the standard, and proposed algorithm estimates the actual parameters with a low error rate even in noisy environments. In addition, SCA has a better convergence performance index than optimization algorithms used in studies in the literature assuming that frequency is known. Performance of the proposed algorithm is also tested on the data obtained from electrical transmission system. SCA estimates the frequencies of harmonics with almost no error, and the amplitude and phase estimation values of each harmonic are in corroboration with the results obtained by the DFT method.

INDEX TERMS Harmonic, harmonic estimation, sine cosine algorithm.

I. INTRODUCTION

In power systems, while frequency components in integer multiples of fundamental frequency are called harmonics, frequency components in non-integer multiples are called inter-harmonic. Extensive use of non-linear loads in power systems such as power electronic devices, photovoltaic systems, and electric arc furnaces (EAF) results in the distortion of pure sine waveforms of current and voltage [1], [2]. In fact, this means that the power quality is impaired. In order to improve the distorted power quality, coordinated control strategies can be applied or the frequencies, amplitudes, and phases of harmonics and sub-inter-harmonics must be rapidly and accurately predicted in accordance with the standards [3], [4]. Thus, the protection of the electrical power system and distribution network is provided. While making harmonic estimation, it should be kept in mind that a maximum of 5% prediction error is allowed by the standard for Class-1 and Class-2 type devices [5].

Moreover, in power systems, the fundamental frequency is not always at its nominal value but varies between 49.5Hz and 50.5Hz. This also causes a change in the frequency of other harmonic and sub-inter-harmonic components. Therefore, the frequency of each harmonic component must be estimated accurately. The accurate estimation of the frequency is very important because, in order to accurately predict the amplitudes and phases of harmonics, the frequencies must be correctly estimated first.

FFT is known as the most popular method in harmonic analysis of static signals in the literature. Many different methods such as wavelet transform, Hilbert Huang Transform (HHT) have been applied to harmonic estimation, because harmonic analysis with FFT yields erroneous results in non-stationary signals or when the signal frequency is not at nominal value that is 50 Hz or 60Hz [6]. The filters used in wavelet transform are not ideal and the modal mixing

The associate editor coordinating the review of this manuscript and approving it for publication was Qiuye Sun.

problems in HHT negatively affect the accuracy of harmonic estimation [6].

Other popular methods used in harmonic analysis are Kalman Filter (KF) and Ensemble Kalman Filter (EnKF) [7], [8]. EnKF has better estimation performance than KF in noisy environments. However, in these methods, the performance of estimation process is determined by the next state matrix corresponding to the matrix of the previous state [9]. In these methods, frequency estimation is completed after amplitude and phase estimation. These algorithms show poor performance at frequency estimation in noisy environments.

MUSIC, Prony's, and ESPRIT methods are also used for harmonic analysis. Although these methods are used in estimating the frequencies, amplitudes, and phases of harmonics, it has been reported that these algorithms are actually more suitable for the frequency identification [10]. If the signal contains harmonic or sub-inter-harmonic components very close to each other, especially in a noisy environment, these algorithms' performance in frequency estimation reduces and they show poor performance in estimating amplitudes and phases [10].

In recent years, the use of optimization algorithms for solving the engineering problems has been increasing [11], [12]. Many hybrid optimization methods have also been applied for the harmonic analysis [13]–[22]. The amplitude and phase values of harmonics and sub-inter-harmonics estimated in [13]–[16] are more 5% of the actual values, which is higher than the maximum error rate specified in the standard [5]. In addition, in these hybrid methods, while phase estimation is performed with heuristics algorithm, Recursive Least Square (RLS) or KF is used for amplitude estimation, which has disadvantages previously stated for KF. In [20]–[22], the authors estimated the amplitudes and phases estimation directly with the optimization algorithm without using a hybrid method.

In all optimization-based algorithms [13]–[22] that are based on KF or RLS, the amplitude and phase estimation is performed by assuming that the frequency of harmonic or sub-inter-harmonic components contained in the signal to be estimated are known. However, in real power systems, if the fundamental frequency and the frequencies of other harmonics and sub-inter-harmonics are not at their nominal values, then the amplitude and phase estimations made by these methods will be false. Therefore, the frequencies of harmonics and sub-inter-harmonics must be accurately estimated first.

In this research work, sine cosine algorithm (SCA) is applied to estimate the power system harmonics and sub-inter-harmonics frequencies, amplitudes and phases. SCA is a heuristic algorithm based on a mathematical model of sine and cosine functions [23]. The author in [23] examined the performance of the SCA algorithm in many test functions and compared it with the best known heuristic algorithms in the literature such as Genetic Algorithm (GA), Bat Algorithm (BA), Firefly Algorithm (FA), and Particle Swarm Optimization (PSO) and observed that the SCA algorithm has a better performance with less computational complexity.

In this study, unlike harmonic analysis using optimization-based algorithms in the literature [13]–[22], it is assumed that the frequencies of the harmonic or inter-harmonic components of the signal are not known. The performance of the SCA has been tested in cases, where the signal contains harmonic and inter harmonic components, at different signal-to-noise ratios (SNR). The results obtained show that the SCA can estimate the model parameters of harmonics and sub-inter-harmonic with less error. Results show that the SCA converges better than several other algorithms, despite the estimation of the frequency increasing the calculation the complexity of the process. The performance of the proposed algorithm has also been tested on field data received from the electricity transmission system. The voltage signal constructed with the SCA algorithm is compared with the actual signal and a very high level of capturing is observed. Estimated frequency, amplitude and phase values of each harmonic obtained by proposed algorithm is compared with the result estimated by DFT and it is seen that the values obtained are similar to each other.

Outstanding features and benefits of the proposed algorithm are given as follows:

- In similar studies in the literature, only amplitude and phase estimation are observed assuming frequency is known. In this study, frequency estimation, which is more difficult, is also taken into consideration.
- This new estimation increased the difficulty of the procedure. However, the estimation of the parameters is performed with less than 5% error.
- Proposed algorithm has a better performance index in noisy environment than some optimization-based algorithms assuming frequency is known.
- SCA algorithm is tested on real field data. It perfectly estimates the frequencies, amplitudes, and phases of the harmonics constituting the signal. Therefore, the proposed algorithm can be easily applied on real systems.
- Adding frequency estimation to the literature may make this study a basis for future studies.
- It is observed that the parameters are not shared in most of the studies in the literature. All parameters used in this study are clearly specified and, thus, paving the way for similar studies in the future.

This paper consists of seven chapters. In the second part, the proposed method is explained. In the third part, the mathematical model of power system harmonic is examined. In the fourth chapter, the results obtained are shared. Fifth chapter presents the performance index of the proposed algorithm. Chapter six includes experiment on field data and, finally, the results of the study are evaluated in the seventh chapter.

II. SINE COSINE ALGORITHM

Sine cosine algorithm (SCA) is a population-based heuristic algorithm based on a mathematical model of sine and cosine functions [23]. Almost all population-based optimization techniques initially generate random solutions to initiate the solution. The search and global optimization process in the space of candidate solutions is different for each optimization technique. Generally, search process is based on positions of candidate solutions or agents. In SCA the positions of the particles are updated by using (1) and (2).

$$X_i^{t+1} = X_i^t + r_1 \sin(r_2) \left| r_3 P_i^t - X_i^t \right| \quad (1)$$

$$X_i^{t+1} = X_i^t + r_1 \cos(r_2) \left| r_3 P_i^t - X_i^t \right| \quad (2)$$

where, P_i^t target position in ith dimension at tth iteration, current position in ith dimension at tth iteration. r_1 is a random number which defines position of next area. r_2 is a random number that determines the how far should be movement towards or away from the target. r_3 is a random number that makes the target point's influence in determining the distance stochastically important or less important by generating a random weight for the target.

$$\begin{cases} X_i^{t+1} = X_i^t + r_1 \sin(r_2) \left| r_3 P_i^t - X_i^t \right|, & r_4 < 0.5 \\ X_i^{t+1} = X_i^t + r_1 \cos(r_2) \left| r_3 P_i^t - X_i^t \right|, & r_4 \geq 0.5 \end{cases} \quad (3)$$

Equations in (1) and (2) are used as given in (3) according to the condition of the r_4 coefficient. Thus, particles come into solution separately in sine and cosine functions. This has a great impact on finding the global best. Thanks to the oscillation motion between the sine and cosine functions, the probability of finding the best solution among all solutions increases. SCA creates and develops a set of random solutions for a specific problem. Therefore, it has the property of avoiding local optimum compared to individual based algorithms. When the sine and cosine functions return to a value greater than or less than 1, different regions of the search space are soughed. The model given in FIGURE 1 shows the change in the sine and cosine function and how to find a solution to update the position inward or outward in the area between another solution and it-self.

The sine and cosine intervals are adaptively changed in order to balance the research process for candidate solutions by using (4). In (4), t is current iteration number, T is maximum iteration number and c is a constant number.

$$r_1 = c - t\frac{c}{T} \quad (4)$$

III. MATHEMATICAL MODELS OF THE POWER SYSTEM HARMONICS

The general form of any discrete-time power signal is described as given in (5).

$$y_{est}[n] = \sum_{j=1}^{M} A_j \cos(2\pi n f_j t + \theta_j) + A_{dc} \exp(-a_{dc} n T_s) + v[n] \quad (5)$$

In (5), Aj, θj, and fj represent the unknown amplitudes phases and frequencies of the harmonics and inter-harmonics, respectively. $A_{dc} \exp(-a_{dc} n T_s)$ is the decaying terms, $v[n]$ is the additive white Gaussian noise, M is the number of harmonic, T_s is the sampling frequency.

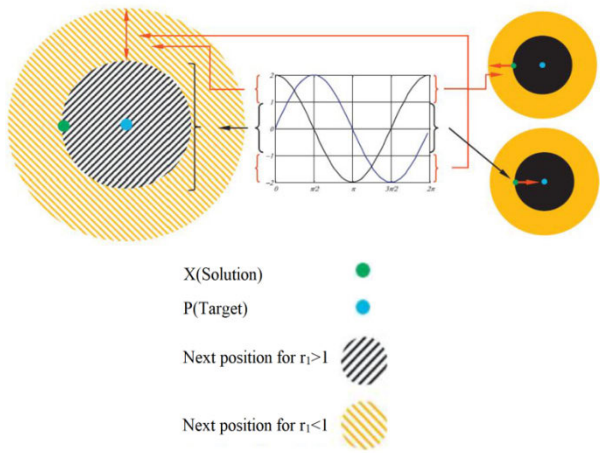

FIGURE 1. Model of sine and cosine function in the range of [-2 2] [23].

In this study, it is assumed that the frequencies of the signal are not known, unlike other heuristic based methods in the literature [13]–[21]. Therefore, the mathematical model defined in [13]–[19] has no significance in this study. Unknown parameters are estimated directly from (5).

In this paper, the performance of SCA for estimating the frequencies, amplitudes and phases of harmonics and sub-inter-harmonics in power systems is investigated. In solving optimization problems, it is necessary to define an objective function (J). In order to optimize the unknown parameters in the harmonic estimation problem, J defined as the difference between actual and estimated signal as seen in (6). Pseudo code of the proposed algorithm for harmonic estimation is given in TABLE 1. Within the scope of harmonic analysis process with SCA algorithm, candidate solutions are created depending on the constraints of the problem first. These candidate solutions are located in the solution space.

TABLE 1. Pseudo code of SCA for parameters estimation of harmonics and inter-harmonics.

SCA
İnitialize candidate search space
While (t<max iteration number)
Evaluate each search agent's fitness value using objective function in (6)
Update the best solution
Update the r_1, r_2, r_3, and r_4
Update the positions of search agents using (3)
Return the best solution ever achieved as a global optimum

Harmonic analysis process is performed by using candidate solutions in solution space. By comparing the solutions obtained with the required result, the fitness value for each candidate solution is determined. Considering these fitness values, the best solution is recorded. Then r_1, r_2, r_3 and r_4 are updated. The positions of the search agents are updated by taking into account the location of the best solution. Finally, it is checked whether the determined maximum number of iterations has been reached. If the maximum number of

TABLE 2. Parameters limits for the harmonic and inter-harmonic estimation using SCA.

Harmonic & Inter-harmonic Component	Lower Limit			Upper Limit			Maximum Number of Iterations	Number of Neighbored
	Amp. (p.u)	Freq. (Hz)	Phase (Degree)	Amp. (p.u)	Freq. (Hz)	Phase (Degree)		
Fund. Comp.	0.1	49.5	60	5	50.5	100	1000	100
3rd Harmonic	0.1	148.5	40	2	151.5	80		
5th Harmonic	0.1	247.5	25	1	252.5	65		
7th Harmonic	0.05	346.5	16	0.8	353.5	61		
11th Harmonic	0.05	544.5	10	1	555.5	50		
Sub Harmonic	0.2	19.5	60	2	20.5	90		
Int.harmonic1	0.1	177	50	0.8	183	80		
Int.harmonic2	0.3	225	5	0.8	235	35		

TABLE 3. Estimation performance of SCA for the signal in (7).

	Parameters	Fund.	3th	5th	7th	11th
Actual	F (Hz)	50	150	250	350	550
	A (p.u)	1.5	0.5	0.2	0.15	0.1
	P (^{0})	80	60	45	36	30
Estimated	F (Hz)	50.08	150.24	250.09	348.46	547.22
	E(%)	0.16	0.16	0.036	0.44	0.505
	A(p.u)	1.4905	0.4871	0.2006	0.1430	0.1005
	E(%)	0.63	2.58	0.3	4.7	0.5
	P (^{0})	77.63	61.95	42.83	40.3	29.05
	E(%)	2.96	3.25	4.82	11.94	3.17

iterations has not been reached, the previous steps are repeated. If the maximum number of iterations is reached, the program is terminated.

$$J = \min \sum_{k=1}^{N} e_k^2(k) = \min \sum_{k=1}^{N} (y_k - y_{kest})^2 \quad (6)$$

IV. SIMULATION RESULTS

In this section, the performance of SCA is tested by creating two different synthetic signals. In the first case, our signal consists only of harmonic components; In the second case, sub-and inter-harmonics are added to the signal. In addition, the performance of the proposed algorithm in both experiments is tested by creating 20db and 10db SNR. In harmonic analyses based on heuristic algorithms in the literature [13]–[22], the lower and upper limits of the amplitudes and phases are not specified. The number of iterations, population size upper and lower limit required for each harmonic or sub-inter-harmonic components for the SCA algorithm during the analysis are shown in Table 2 to contribute to future studies. In this research work, the lower limits of the amplitudes are chosen approximately one-fifth of the real values and approximately four times the real values at the upper limits. At the lower and upper limits of the phases, 20^o below and above the actual values are selected, respectively. Since the nominal value of the fundamental frequency in power systems ranges between 49.5Hz and 50Hz, the lower and upper limit of the frequency of the fundamental component has been chosen as 49.5 and 50Hz in the analysis. The lower and upper limits of other harmonics and sub-inter-harmonics are determined according to the multiples of this lower and upper limit value.

The SCA algorithm is ran 50 times for each analysis and the average results are recorded. In the synthetic signals, the fundamental frequency and sampling frequency (f_s) are selected as 50Hz and 2000Hz, respectively, and the unit of amplitude is per unit (p.u). Although the number of iterations in the algorithm is determined as 1000, estimated parameters do not change after the 100 iterations. Therefore, the values of the parameters estimated in the simulation results are shown up to the 100 iterations.

A. EXPERIMENT 1

As can be seen in (7), in the first part of the analysis, the synthetic signal which is used in the literature to represent the time varying power signal consists of fundamental components, third, fifth, seventh, eleventh harmonics, a decaying terms, and 0.01 random noise [20].

$$\begin{aligned} y(t) = {} & 1.5sin(2\pi f_1 t + 80^\circ) + 0.5sin(2\pi f_3 t + 60^\circ) \\ & + 0.2sin(2\pi f_5 t + 45^\circ) + 0.15\sin(2\pi f_7 t + 36^\circ) \\ & + 0.1sin(2\pi f_{1_1} t + 30^\circ) + 0.5exp(-5t) + \mu(t \end{aligned} \quad (7)$$

The proposed algorithm is first ran on the synthetic signal given in (7). Estimation results and percentage errors are shown in TABLE 3, F, A, P, and E in the table represent frequency, amplitude, phase, and percent error, respectively. When the table is examined, it is seen that all percent errors

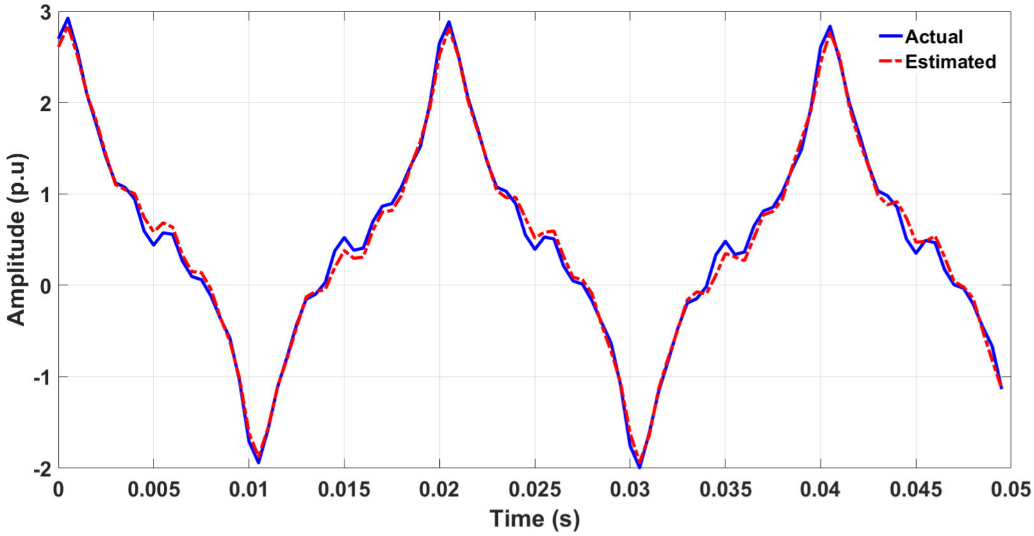

FIGURE 2. Actual signal given in (7) and estimated signal by SCA.

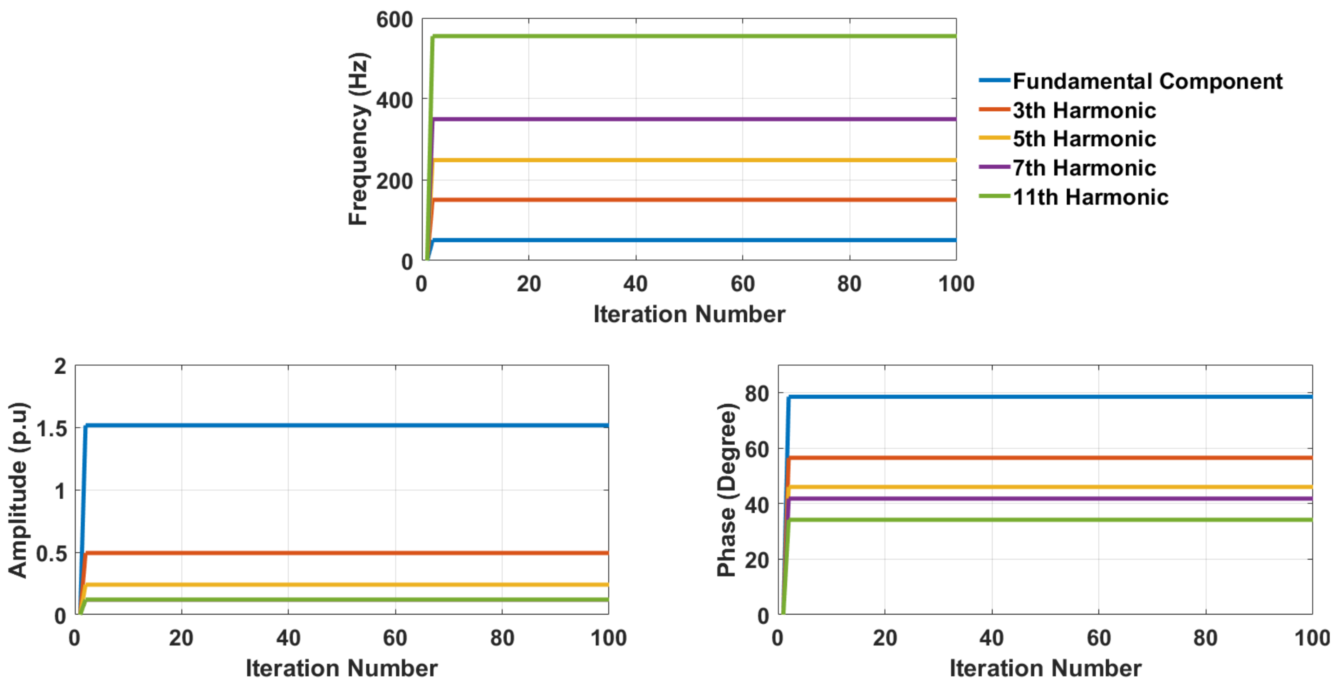

FIGURE 3. Estimated frequencies, amplitudes and phases of harmonics by SCA.

except the phase error of the 5^{th} harmonic are far below the maximum error rate which is 5%percent determined by the standard [5]. The actual signal and the reconstructed signal obtained by SCA are show in plotted on top of each other and shown in FIGURE 2. When the FIGURE 2 is examined, it is seen that the real signal and the structured signal overlap with small error rate. FIGURE 3 shows the estimation results of frequencies, amplitudes, and phases of all harmonics. Estimation of frequencies, amplitudes, and phases reach the actual values before the 20 iterations.

The performance of the proposed algorithm is analyzed at 20db and 10db SNR conditions. As the noise ratio increased, performance of the SCA algorithm to overlap the actual signal decreases as shown in FIGURES 4 and 6. Convergence of frequencies, amplitudes, and phases are illustrated in FIGURES 5 and 7 at 20dB and 10dB SNR, respectively. As can be seen, the estimations made for frequencies, amplitudes, and phases reached their corresponding values before the 40 iterations. When FIGURES 5 and 7 are examined, as the SNR value decreases, the SCA algorithm has better

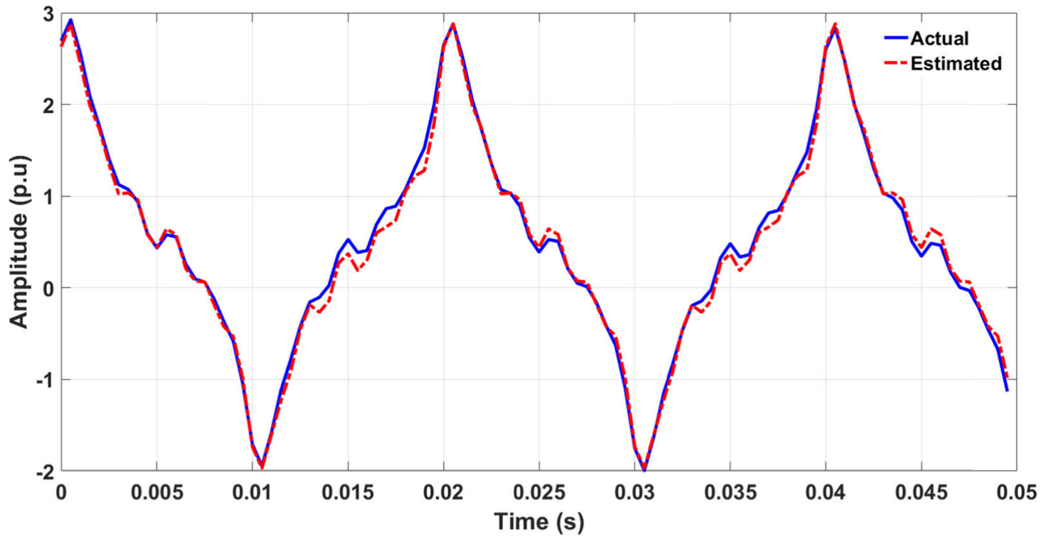

FIGURE 4. Actual signal given in (7) and estimated signal at 20dB SNR by SCA.

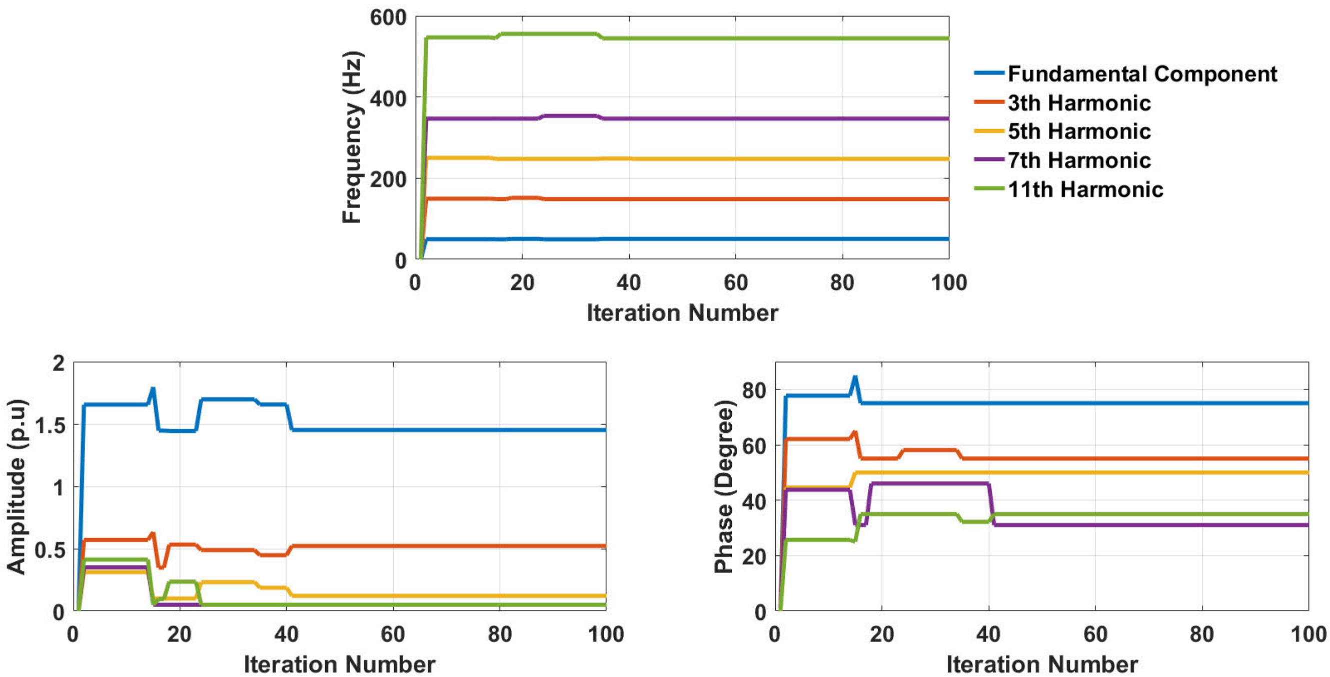

FIGURE 5. Estimated frequencies, amplitudes and phases of harmonics at 20dB SNR by SCA.

performance to estimate frequencies and amplitudes than the phase estimation.

B. EXPERIMENT 2

In this section, the signal in (8) is generated by adding sub harmonic and two inter-harmonics at 20Hz, 180Hz, and 230Hz to the synthetic signal in (7). In order to test the performance of the SCA algorithm, the same analyzes as in Experiment 1 are also made in this section.

$$\begin{aligned} y(t) &= 0.505sin(2\pi 20t + 75^\circ) + 1.5sin(2\pi f_1 t + 80^\circ) \\ &+ 0.5sin(2\pi f_3 t + 60^\circ) + 0.25sin(2\pi 180t + 65^\circ) \\ &+ 0.35sin(2\pi 230t + 20^\circ) + 0.2sin(2\pi f_5 t + 45^\circ) \\ &+ 0.15\sin(2\pi f_7 t + 36^\circ) + 0.1sin(2\pi f_{1_1} t + 30^\circ) \\ &+ 0.5exp(-5t) + \mu(t) \end{aligned} \tag{8}$$

The proposed algorithm is ran on the synthetic signal given in (8) with 0.01 random noise. Estimation results and percentage errors obtained are listed in TABLE 4. When the percentage error values in TABLE 4 are examined, the prediction error in the amplitudes and phases of the 7th and

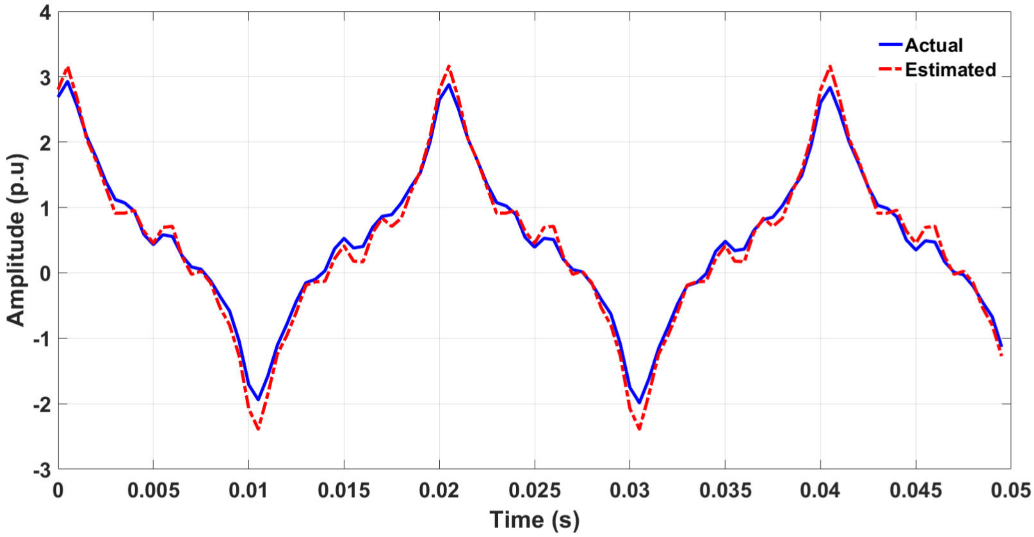

FIGURE 6. Actual signal given in (7) and estimated signal at 10dB SNR by SCA.

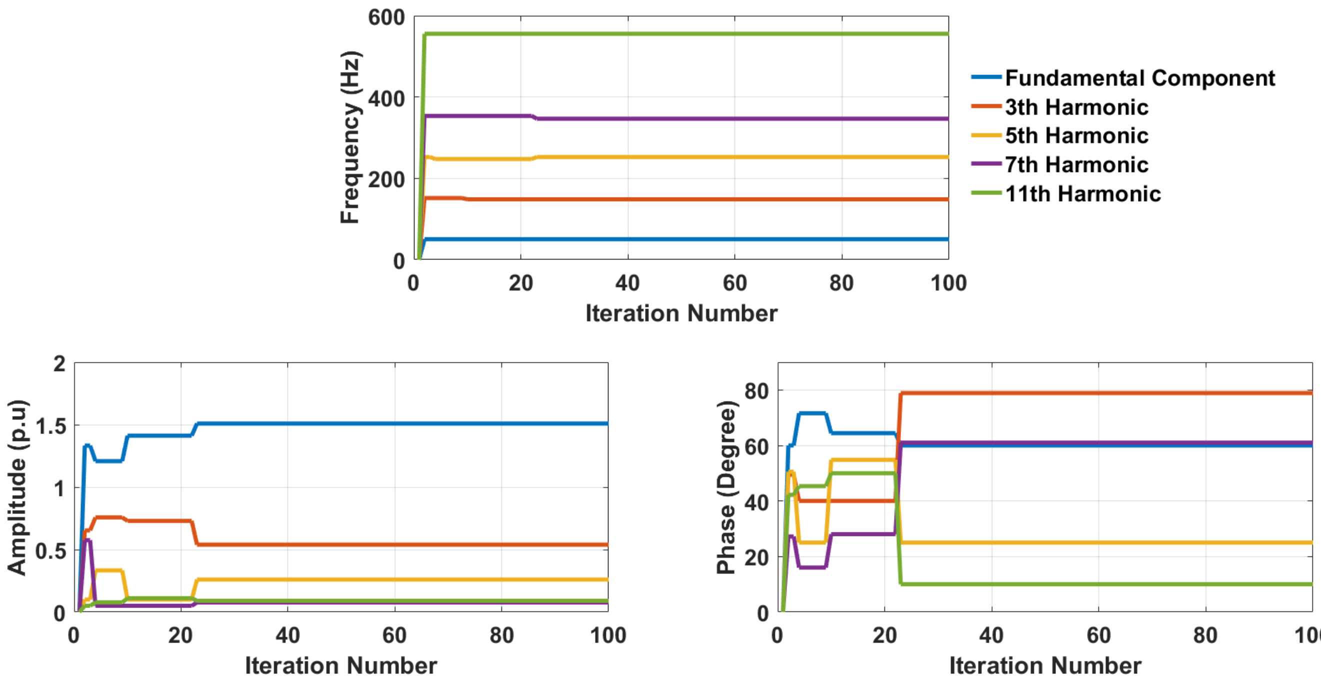

FIGURE 7. Estimated frequencies, amplitudes and phases of harmonics at 10dB SNR by SCA.

11^{th} harmonic and the amplitude of the 5^{th} harmonic exceeds the error limit set by the standard [5]. All values other than these are below the error limit set by the standard. SCA algorithm shows sufficient performance to estimate the parameters of the sub-inter-harmonics, fundamental component, and third harmonic. In addition, the estimated signal follows the real signal with a small error rate as seen FIGURE 8. FIGURE 9 shows the estimated frequencies, amplitudes, and phases of harmonics by SCA. According to this graph, the estimation of the frequencies occurred before 20 iterations, while the estimation of the amplitude and phases is completed in approximately 70 iterations.

The performance of the SCA is tested by adding different noise ratios (20dB and 10dB SNR) to the signal in (8). As seen in FIGURES 10 and 12, as the SNR value decreases, although the error rate between the actual and estimated signal increases, the estimated signal is very similar to the actual signal. Based on FIGURES 11 and 13, in the case of 20dB and 10dB SNR conditions, the parameters of harmonics and sub-inter-harmonics are realized before 80 iterations. As the SNR

TABLE 4. Estimation performance of SCA for the signal in (7).

	Parameters	Sub	Fund.	3th	5^{th}	7^{th}	11^{th}	Int1	Int2
Actual	F (Hz)	20	50	150	250	350	550	180	230
	A (p.u)	0.505	1.5	0.5	0.2	0.15	0.1	0.25	0.35
	P (^{0})	75	80	60	45	36	30	65	20
Estimated	F (Hz)	20.02	50.38	149.31	247.5	351.66	550.33	179	231.56
	E(%)	0.1	0.76	0.46	1	0.474	0.06	0.555	0.678
	A(p.u)	0.4806	1.5119	0.5116	0.247	0.1594	0.08	0.2542	0.3348
	E(%)	4.83	0.79	2.32	23.5	6.27	20	1.68	4.34
	P (^{0})	76.96	76.42	60.796	44.58	42.628	33.65	67.523	15
	E(%)	2.613	4.47	1.316	0.933	18.4	12.16	3.88	25

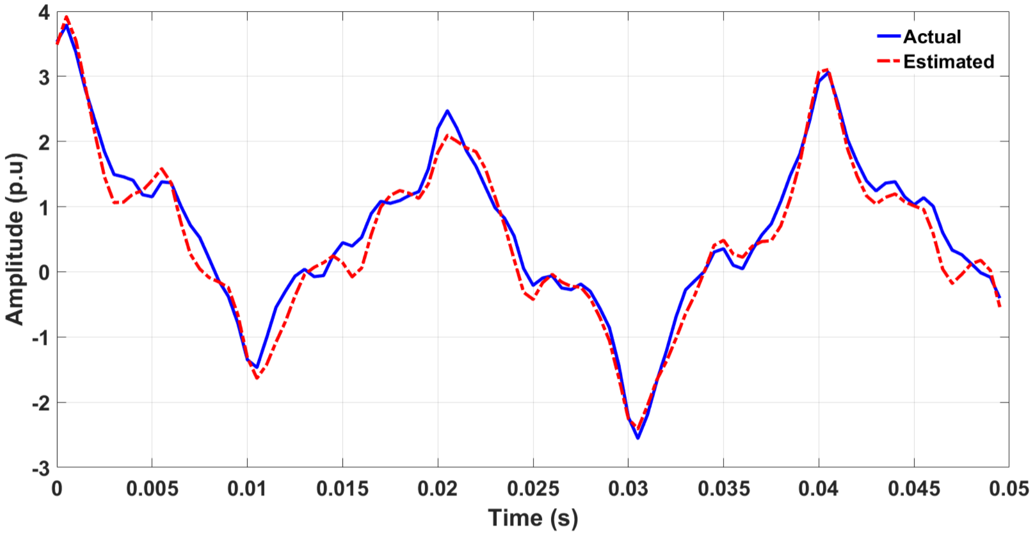

FIGURE 8. Actual signal given in (8) and estimated signal by SCA.

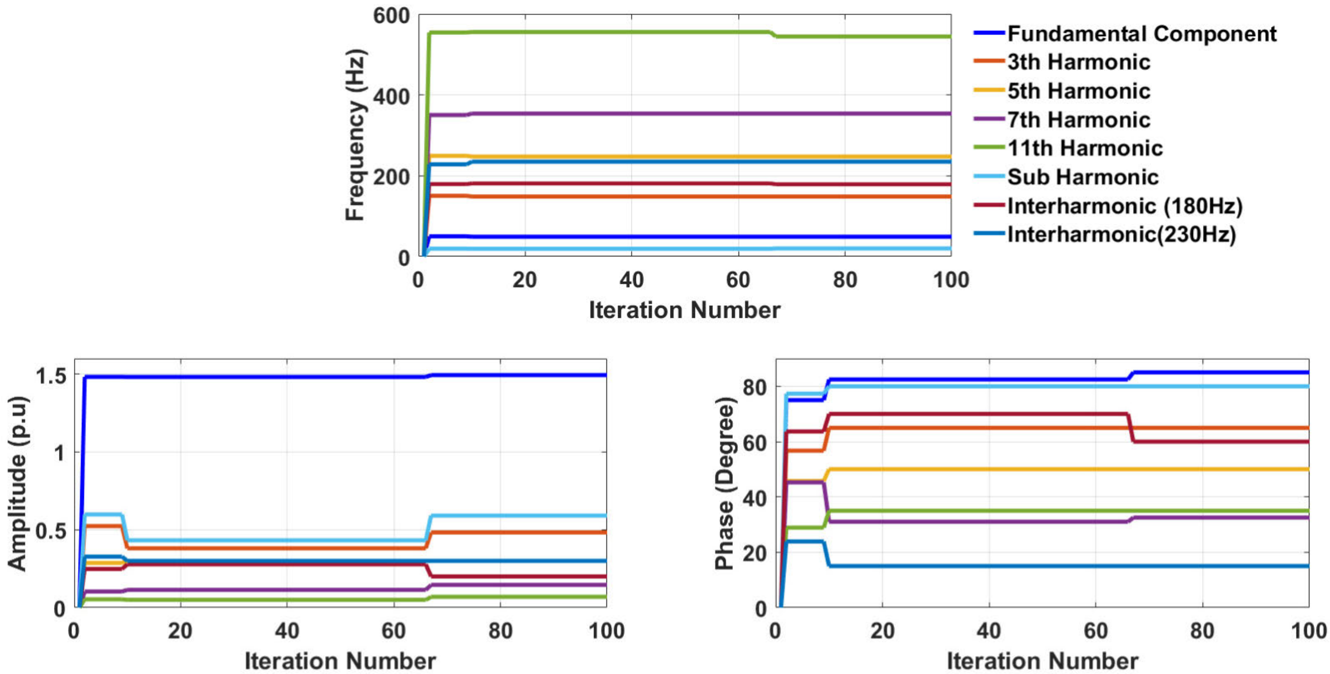

FIGURE 9. Estimated frequencies, amplitudes and phases of harmonics and sub-inter-harmonics by SCA.

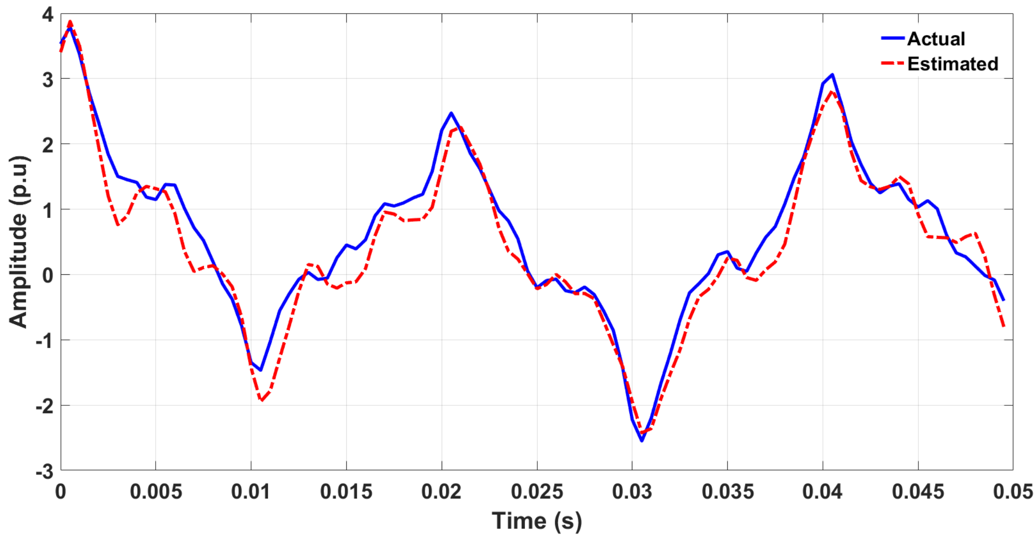

FIGURE 10. Actual signal given in (8) and estimated signal at 20dB SNR by SCA.

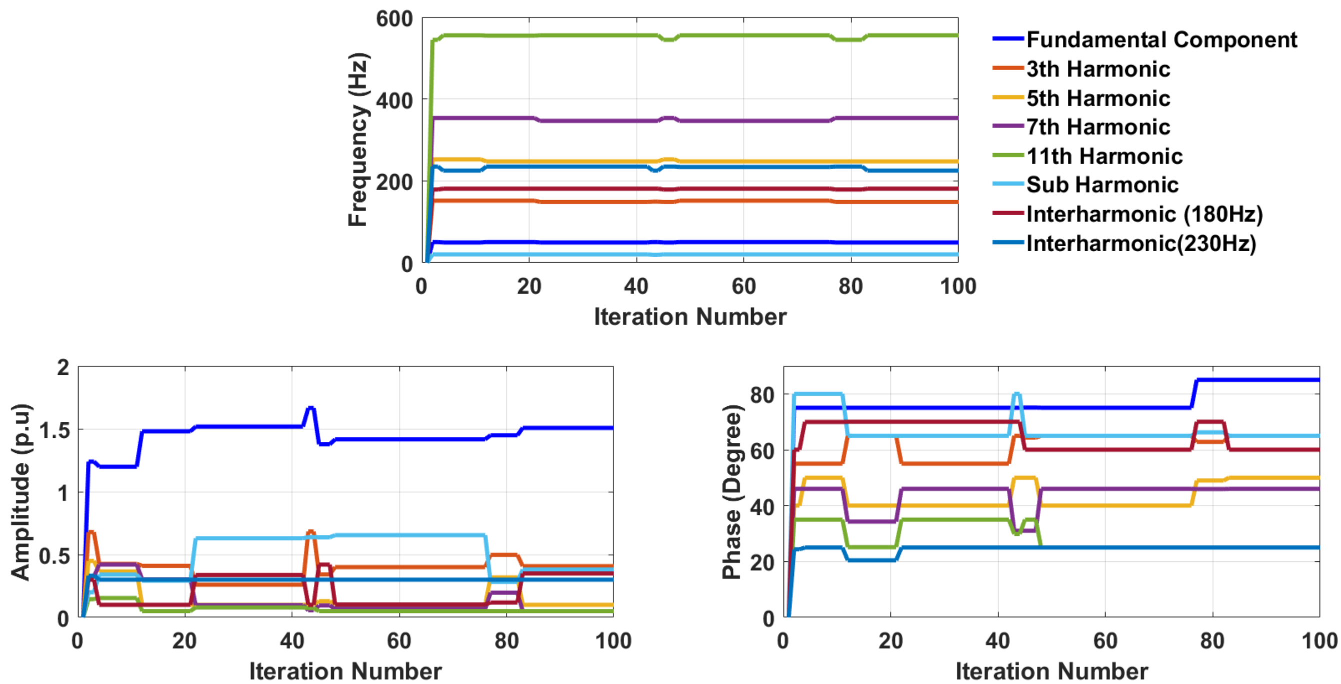

FIGURE 11. Estimated frequencies, amplitudes and phases of harmonics and sub-inter-harmonics at 20dB SNR by SCA.

value decreases, it is seen that the estimation performance of SCA decreases, especially in phase estimation, as shown in FIGURES 11 and 13.

When the first and the second experiment cases are compared, a decrease is observed in the performance of the algorithm when it contains sub-inter-harmonics. In the sub-inter-harmonic case, the percentage error rate is higher in frequency estimation. The frequency percentage estimation errors for the fundamental component and third and fifth harmonic components in the signal in (7) is 0.16, 0.16 and 0.036, respectively, according to TABLE 3. In the sub-inter-harmonic case, these values increased to 0.76, 0.46 and 1, respectively, as shown in TABLE 4. This is because the sub-inter-harmonics added are close to the fundamental component and third and fifth harmonics. The increase in the frequency estimation error causes an increase in the error of the harmonic and sub-inter-harmonic amplitude and phase estimation.

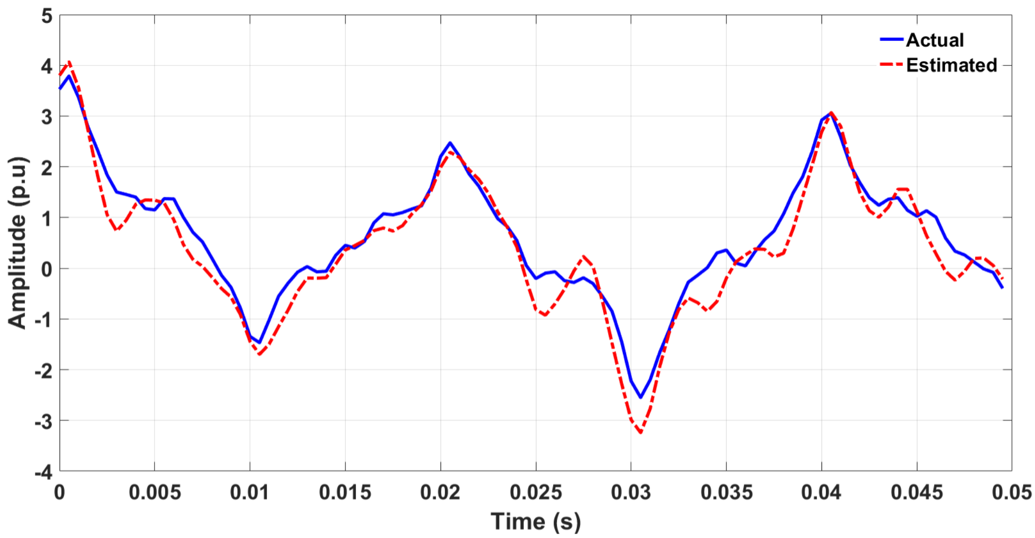

FIGURE 12. Actual signal given in (8) and estimated signal at 10dB SNR by SCA.

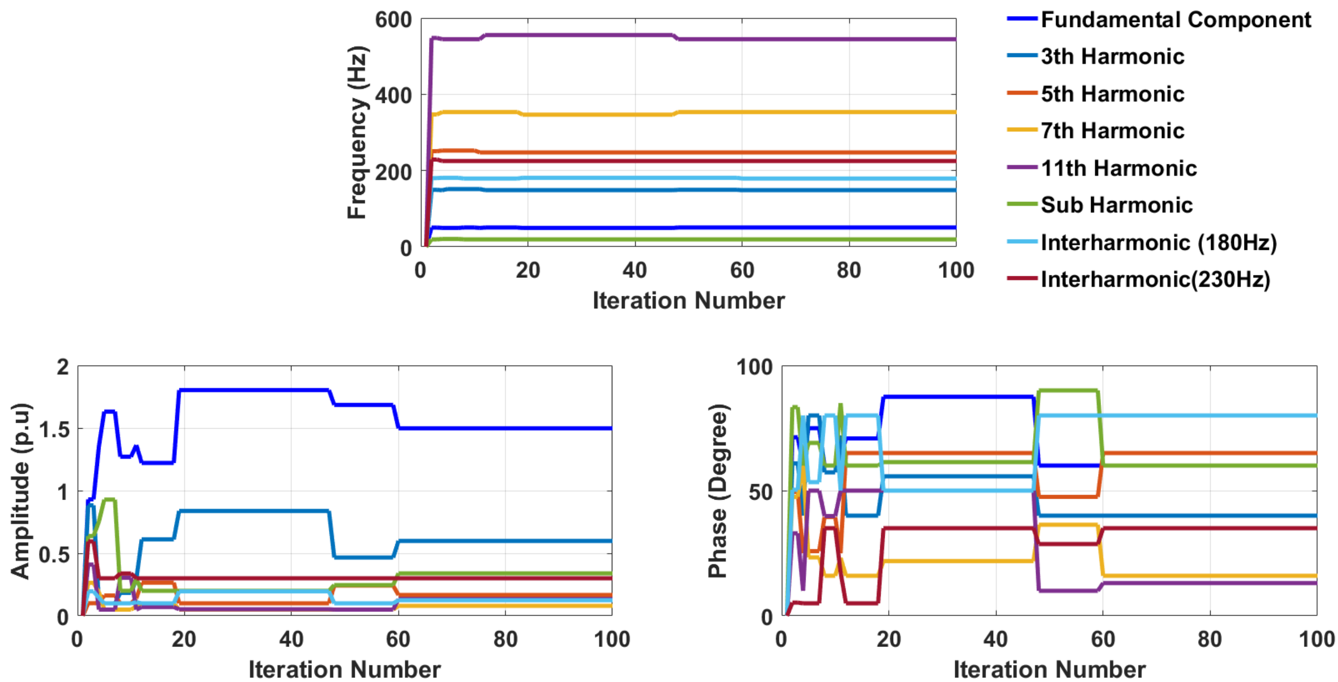

FIGURE 13. Estimated frequencies, amplitudes and phases of harmonics and sub-inter-harmonics at 10dB SNR by SCA.

V. PERFORMANCE INDEX OF PROPOSED ALGORITHM

Performance index (ζ) of the proposed algorithm for the signal in (8) is obtained by the (9) and shown in the TABLE 5. In (9), y[n] is the original signal, y_{est}[k] is the predicted output signal, and N is the number of samples. It shows the performance index of the method proposed in TABLE 5.

$$\zeta = \frac{\sum_{n=1}^{M} (y[n] - y_{est}[n])^2}{\sum_{n=1}^{M} (y[n])^2} \times 100 \tag{9}$$

TABLE 5. Performance indices of SCA for the signal in (8).

SNR Values	Proposed Algorithm	GA-LS. [20]	PSO-LS [20]
20dB	5.3121	1.2037	0.9546
10dB	7.3152	7.3645	10.6537

It is assumed that the frequencies of harmonics are known in the amplitude and phase estimation made by optimization based algorithms in the literature. In this study, although the frequency is also estimated with the proposed algorithm,

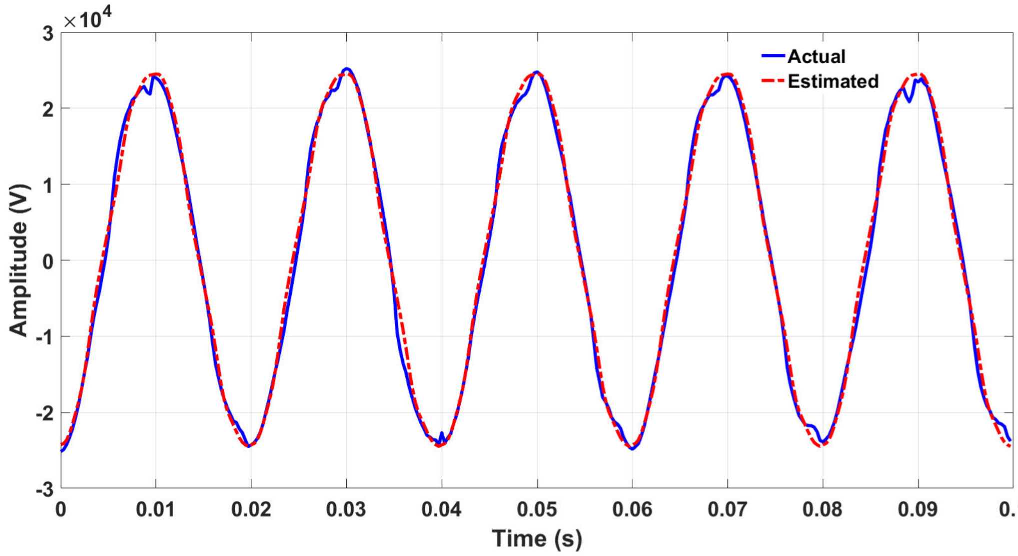

FIGURE 14. Voltage signal obtained from the electrical transmission system and estimated output signal by SCA.

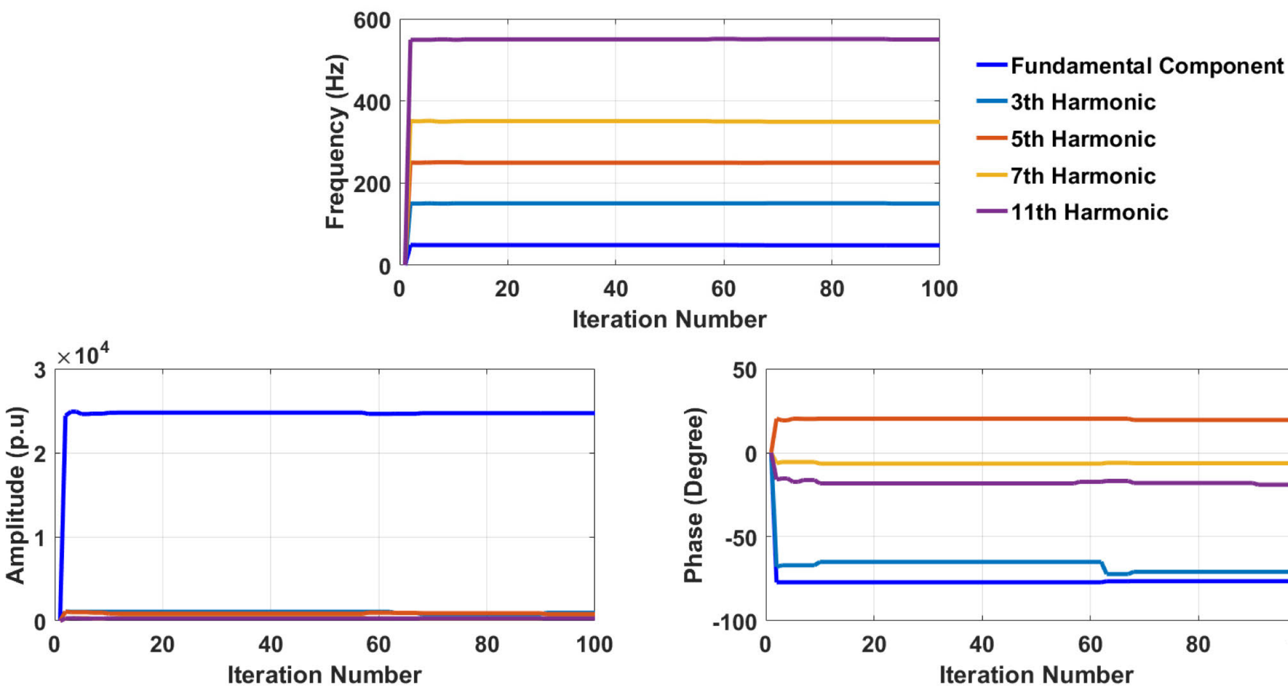

FIGURE 15. Estimated frequencies, amplitudes and phases of the voltage signal obtained from the electrical transmission system by SCA.

it has a better performance index than the algorithms shown in TABLE 5. According to this table, Genetic Algorithm Least Square (GA-LS), Particle Swarm Optimization Least Square (PSO-LS) algorithms have worse performance index than the proposed algorithm at 10dB SNR.

VI. EXPERIMENT ON FIELD DATA

In order to test the performance of SCA on real signals collected from the power system in the field, harmonic analysis has been performed on the 0.1 second voltage data obtained from the electrical transmission system with the proposed algorithm. The sampling frequency of the voltage data is 3200Hz and the voltage level is approximately 25 kV AC as shown in FIGURE 14. In order to prove the validity of the analysis results, the analysis is also performed by DFT method. In FIGURE 14, it is seen that the reconstructed signal obtained by SCA follow the real signal with a negligible error. FIGURE 15 shows the frequencies, amplitudes, and

TABLE 6. Comparison of the DFT and SCA in terms of harmonic parameters estimation.

	Parameters	Fund.	3th	5th	7th	11th
DFT	F (Hz)	50	150	250	350	550
	A (V)	24.58k	1.05k	935	291	290
	P (^{0})	-80.75	-68.90	22.27	-5.18	-16.20
SCA	F (Hz)	49.95	150.08	250.7	349.7	549.8
	A (V)	24.84k	0.87k	890	300	196
	P (^{0})	-78.35	-67.52	19.94	-9	-18

phases estimation of the voltage data. The same analysis is performed with the DFT method and obtained results are compared with the results found with the proposed algorithm and shown in TABLE 6. According to this table, the results obtained by SCA and DFT are nearly same and SCA shows superior performance in estimating the frequencies, amplitudes, and phases of the signal. Proposed algorithm can find the signal parameters before 20 iterations.

VII. CONCLUSION

In power systems, the value of the fundamental frequency ranges changing between 49.5Hz and 50.5Hz causes the frequency of other harmonic components in the signal to not be at its nominal value. In order to improve the power quality frequencies, amplitudes, and phases of harmonics and sub-inter-harmonic must be estimated accurately. In this study, a sine cosine algorithm is used to estimate the model parameters of a time- varying power signal contain harmonics and sub-inter-harmonics. Unlike the optimization-based algorithms used for estimation of harmonics and sub-inter-harmonics in the literature, it is assumed in this study that the frequencies of harmonics and sub-inter-harmonics are not known. The performance of the proposed algorithm is tested on the signal containing harmonics and then adding sub-inter-harmonics to this signal at different noise levels. According to the results, although the performance of the proposed algorithm decreases as the noise ratio in the signal increases, the predicted signal captures the real signal with a small error rate. When the performance of SCA in harmonic and sub-inter-harmonic signal conditions are compared, in the sub-inter-harmonic cases, it is observed that, if the frequency components in the signal are close to each other, SCA has a slightly poor performance in estimating the real frequencies values. Even if a decrease in its performance is observed in the sub-inter-harmonic case, the proposed algorithm has a better performance index than some optimization-based algorithms used for the estimating the model parameters of harmonics by assuming that the frequencies are known in the literature.

Moreover, the proposed algorithm is examined using the field data obtained from the electrical transmission system, which contains only harmonic components. In order to prove the accuracy of the results, the same analysis is also performed using DFT. It has been observed that the actual signal and the estimated output signal overlap accurately. Also, SCA can estimate actual frequency values with very small error. When the obtained estimated amplitude and phase values compared with DFT, it is seen that the results found are very similar.

According to the obtained results, SCA algorithm has sufficient performance in estimating the parameters of harmonics and sub-inter-harmonics in power systems to improve the power quality. The proposed algorithm can be used easily in real power systems.

To improve the performance of SCA in frequency estimation in the sub-inter-harmonic cases, it is planned to work on the hybrid optimization algorithm to estimate the frequencies better to increase the accuracy of amplitude and phase estimation.

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