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Interharmonics estimation using hybrid multi sine cosine algorithm

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Abstract

The existence of nonlinear loads and switching converters for wind and solar energy systems create distorted sinusoidal waveforms in power systems. The distorted signals are comprised of harmonic and inter harmonic frequency sinusoidal components that create disturbances like flicker, overheating of equipment, electrical losses, control system and digital meter faults, weakening of electrical appliances and electromagnetic interferences with other apparatus. Accurate measurement of the inter harmonic distortion is significant to determine the quality of the power delivered. A novel method presented in this paper has been developed based on the hybridization of the sine wave correlation technique and multi sine-cosine algorithm (SWC-MSCA) for the estimation of inter harmonics. The suggested algorithm is validated with a standard power system test signal and compared with the other on similar competent algorithms given literature. The proposed estimator outperforms pertaining to exactness and computing effort. The suggested estimator is also employed for the prediction of inter harmonics on a grid-tied single-phase PV system.

Keywords: Interharmonics, sine wave correlation, multi sine cosine algorithm, power quality, estimation
2020 MSC: Primary 90C33, Secondary 26B25

1 Introduction

Nonlinear switched loads and sources like switching converters present in variable Induction or synchronous motor speed drives, SMPS, energy efficient lamps, arc furnaces and interfacing converters that connect renewable energy sources to the grid, might produce distortions in the regular sinusoidal current and voltage waveforms. The distorted waveform may be distinguished by periodic products of integer and non-integer sinusoidal fundamental frequency. When connected to the grid, power converters cause a spike in harmonic distortion due to consumption and production at frequencies other than the system's fundamental frequency. Power quality is one of the primary concerns with the rapid growth of grid tied PV systems. One possible root-cause of interharmonic emissions transferred to the grid current in PV inverters could be associated to the Maximum Power Point Tracking (MPPT) management. This becomes evident due to the saturation of the P–V curve at very low-power working modes [11]. One of the main reasons of interharmonics is the perturbation caused by the MPPT algorithm. The perturbation step-size of the MPPT algorithm is said to have a significant impact on the amplitudes of the interharmonic components. The MPPT sampling rate, on the contrary, has an impact on both the amplitude and frequency of the interharmonics [14].

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Interharmonics are also caused by dynamic changes in solar insolation caused by fast cloud passages and ramping rate actions in large PV plants [9]. Hence, the interharmonic frequencies are greatly influenced by the amplitudes of the MPPT sampling rate as well as the instantaneous MPPT perturbations.

Interharmonics might have a number of drawbacks, including flicker, overheating of equipment, electrical losses, errors in control systems and digital meters. They also create difficulties like, harmonic instabilities and sub-synchronous oscillations during cascading operation of multiple inverters; overlapping of harmonic and interharmonic components generating irregular frequencies; PLL based PV inverters becoming erratic; production of resonant frequencies that are not in tune with harmonic frequencies; tripping of protective circuits involuntarily, and so on. Interharmonics can cause the protection circuit to trip, disconnecting PV systems from the grid [7]. This will result in significant energy losses. As a result, it's critical to precisely assess their presence in grid voltage and current.

In the literature, several approaches of harmonic estimation employing similar linear system models have been reported. The most often used methods for calculating interharmonics are the fast algorithms derived from the discrete Fourier transform (DFT). The DFT-based algorithms suffer from aliasing, seepage, and picket fence phenomena under certain unfavorable situations. [21] predicted another type of harmonic pollution that the DFT is unable to detect, is frequency deviation. [19] proposed a technique that outperforms DFT, but it necessitates prior knowledge of the deviating frequency estimate. The Kalman filtering method was utilized to evaluate various states and parameters of harmonics [2, 3]. This method is straightforward, linear, and reliable; however, it necessitates prior knowledge of the electrical signal's statistics, as well as a precise definition of the state matrix.

The two parameters, amplitude and phase, are extremely important for building filters to eliminate and reduce interharmonics and their consequences. Because frequency changes over time, the traditional estimation method based on constant frequency modelling, which assumes that the voltage waveform in the power system is completely sinusoidal and frequency is determined by the time between two zero crossings., is greatly impacted. As a result, quick methods for predicting and measuring harmonic signals are necessary.

Hybrid approaches based on population search algorithms such as Genetic Algorithm [15, 4, 12, 1, 13] have been used to evaluate the harmonic components contained in voltage/current waveforms in power systems. In these hybrid methods, the phase of the harmonic components of the power signal is optimized using metaheuristic method., and the amplitude of the harmonic signal is then determined using standard recursive least squares. These combined methods provided improvement in estimation performance such as reduction of assessment error, less computation time and attaining improved performance in presence of inter and sub-harmonic components. Because there are more local optimal solutions while estimating interharmonics, a technique for addressing optimization problems with multiple local minimums is required. With a clustered population of solutions, the algorithm should strike a balance between exploration and exploitation. In this paper a maiden attempt has been made for the accurate estimation of interharmonics using a hybridized approach combining the Sine Wave Correlation and Multi Sine-Cosine Algorithm (SWC-MSCA). The suggested method employs a sine-fitting strategy to decrease noise and sine wave correlation to determine signal amplitude, and phase using cosine and sine signals for correlation, as well as MSCA to provide an accurate estimation of the interharmonics. The proposed SWC-MSCA is easy, flexible, and simply implemented. The proposed method has proven to be effective in solving harmonic estimate situations in which the number of harmonics present in the signal is unknown. The simulation results reveal that the suggested hybrid algorithm outperforms the above-mentioned competing methods in terms of overall performance. The following is a breakdown of the paper's structure. The first section contains an introduction and a review of the literature. The MSCA algorithm is described in depth in Section 2. The estimation of interharmonic using the SWC–MSCA algorithm is presented in Section 3. Section 4 discusses the simulation results and Section 5 has the conclusion.

2 Multi Sine Cosine Algorithm

[8] invented the Sine-Cosine algorithm (SCA), a metaheuristic search method based on the sine and cosine functions in trigonometry. Using a mathematical model based on sine and cosine functions, the SCA generates numerous random solutions at first and encourages them to choose the best option. In 2021, [14] suggested MSCA (Multi Sine Cosine Algorithm) to avoid local optima convergence and promote exploitation. The sine or cosine function is given in equation 2.1 or equation 2.2 correspondingly, and the algorithm operates by looking for solutions in the search space.

$$Z_i^{t+1} = Z_i^t + x_1 * sin(x_2) * |x_3 P_i^t - Z_i^t| \tag{2.1}$$

$$Z_i^{t+1} = Z_i^t + x_1 * cos(x_2) * |x_3 P_i^t - Z_i^t| \tag{2.2}$$

where Z_i^t denotes the positions of the present i^{th} solution at t^{th} iteration. x_1, x_2 and x_3 are the random variables. P_i is the destination solution and the symbol || denotes the absolute value. The equation 2.1 and equation 2.2 are unified into one function in equation 2.3:

$$Z_i^{t+1} = \begin{cases} Z_i^{t+1} = Z_i^t + x_1 * sin(x_2) * |x_3 P_i^t - Z_i^t| & \text{if } x_4 < 0.5 \\ Z_i^{t+1} = Z_i^t + x_1 * cos(x_2) * |x_3 P_i^t - Z_i^t| & \text{if } x_4 >= 0.5 \end{cases} \tag{2.3}$$

where x_4 is a number between 0 and 1 that is chosen at random. The parameter x_1 is a random number that determines the size of the area of the following solution, that could be either outside or inside the space between Z_i and P_i. To strike a balance between exploration and exploitation, the parameter, x_1 is adjusted using the equation below.

$$x_1 = d - t\frac{d}{T} \tag{2.4}$$

where, d is a constant, the total number of iterations is T, and the current iteration is t. The parameter x_2 specifies how far should the movement be towards or away from the goal. The parameter x_3 is a random weightage for the target that is used to stochastically emphasize ($x_3 > 1$) or deemphasize ($x_3 < 1$) the target's significance in calculating the distance. The parameter, x_4 indicates equal switching between the sine and cosine parts, as seen in equation 2.3. The haphazard groupings of search agents i.e., $Z_1, Z_2, Z_3, \ldots, Z_n$ of equal sized population N, where each cluster $Zi = [z_{i1}, z_{i2}, z_{i3}, \ldots, z_{in}]$ are initialized to provide a comprehensive solution to the specified problem. These clusters are then united to form a single group Z that provides a superior solution. The execution of MSCA is explained in the following algorithm.

1. Random population groupings $Z_1, Z_2, Z_3, ..., Z_n$ are created at the start.

2. The value of x_1 is decreased from 2 to 0 over time.

3. If the value of $x_1 > 1$, more diversity is provided in the new single solution by merging all of the clusters using the greatest Euclidean distance as

$$Z_{1,n} = \max ELD(Z_1, Z_2, Z_3, \ldots, Z_n) \tag{2.5}$$

4. If the value of $x_1 < 1$, more diversity is provided in the new single solution by merging all of the clusters using the minimum Euclidean distance as

$$Z_{1,n} = \min ELD(Z_1, Z_2, Z_3, \ldots, Z_n). \tag{2.6}$$

5. The objective function $f(Z)$ is used to evaluate each of the search agent clusters.

6. The best solution from all the clusters found so far is updated. ($P = Z$).

7. The random numbers x_1, x_2, x_3 and x_4 are updated.

8. Equations 2.5 and 2.6 are used to calculate the position of search agents.

9. The steps above are repeated until all of the conditions are satisfied or the iterations are completed.

The proposed MSCA algorithm improves on the SCA algorithm in two phases: the first phase introduces a clustered population to diversify and intensify the search in order to avoid local minima. In the second phase, during the update process, MSCA looks for better clusters that successfully give convergence to global minima. When compared with other evolutionary algorithms, the variables x_1, x_2, x_3 and x_4 that decide the convergence of algorithm are automatically adjusted and are independent of initial values.

3 Interharmonic Estimation using SWC–MSCA

In the proposed hybrid method, the first estimates of frequencies and their corresponding magnitudes and phases are extracted using sine wave correlation (SWC). Then the magnitudes and phases are adjusted precisely to estimate interharmonic and harmonic components using MSCA so as to minimize the error between the actual and estimated signals. Any noise contaminated periodic signal can be organized in the following way:

$$u(t) = \sum_{n=1}^{N} A_n sin(w_n t + \phi_n + \gamma(t)), \tag{3.1}$$

N is the number of harmonics in the system., $w_n = 2\pi f_0$, f_0 is the fundamental frequency and $\gamma(t)$ is the noise that is added to the signal. Accurate amplitude and phase estimation becomes more challenging in noisy environments. The influence noise in the estimation of signal can be largely reduced by using sine-fitting techniques. The simpler form of sine-fitting that can be used to fit a wave is defined as:

$$u(t) = A_c cos(2\pi f t) + A_s sin(2\pi f t) + A_{DC} \tag{3.2}$$

where A_c and A_s are the in-quadrature sine amplitudes of the sine wave, f is the frequency of excitation and A_{DC} is the DC element. If a single frequency signal is utilized for excitation, sine wave correlation (SWC) can be used to recover the signal amplitude from the obtained data set. Phase information may be retrieved using cosine and sine signal correlation. [16]. Sine wave correlation is a general method for identifying the content of a sine wave in an input signal of a specific frequency and phase. This process is the foundation of the Fourier transform, and computing techniques established for general signal analysis can be used to discover the components of the signal produced when a sine wave is applied to system input. The process for determining amplitude and phase can be simplified to make it more computationally efficient. The function 3.2 is fitted to the set of M samples,$u_1, u_2, \ldots, u_M$, attained at a frequency f_s at time intervals $t_1, t_2, \ldots, t_M$, is realized as:

$$A_C = \frac{\sum_{m=1}^{M} [cos(2\pi f t_m).u_m]}{\sum_{m=1}^{M} [cos(2\pi f t_m)]^2} \tag{3.3}$$

$$A_S = \frac{\sum_{m=1}^{M} [sin(2\pi f t_m).u_m]}{\sum_{m=1}^{M} [sin(2\pi f t_m)]^2} \tag{3.4}$$

$$A_{DC} = \frac{\sum_{m=1}^{M} u_m}{M}. \tag{3.5}$$

Then the measured signal magnitude is given as

$$A = \sqrt{A_C^2 + A_S^2} \tag{3.6}$$

and the phase is given by

$$\phi = arctan\left(\frac{A_S}{A_C}\right). \tag{3.7}$$

Here the SWC algorithm is first implemented for the extraction of frequencies and their corresponding magnitude and phases. The vector of variables $A_1, A_2, \ldots, A_n$, and $\phi_1, \phi_2, \ldots, \phi_n$, is given as input to the MSCA based optimization algorithm. The estimation problem's objective function ϵ, which will be used to optimize the variables, may then be represented as

$$minimize \epsilon = \left(\sum_{n=1}^{N} (u_n - u_{n_{est}})^2\right), \tag{3.8}$$

where, u_n is the actual harmonic signal observed on the electrical grid and $u_{n_{est}}$ represents the predicted values of the harmonic signal. Figure 1 shows the integration of SWC with MSCA methodology for the estimation of interharmonics in power system.

4 Case study

For the estimate of amplitude and phase, the suggested hybrid SWC-MSCA has been applied for test signals for both under normal and noisy situations and the results were compared to those of other metaheuristic methods proposed in the literature.

The hybrid methodology is used in two separate harmonic estimation case studies. In the first one, a test signal consisting of power electronic devices, electronic blasts and non-linear systems, containing of harmonics with inter and subharmonics, reported in literature is considered and the estimation is carried out. As a power signal disrupting effect, additive white gaussian noise components are used, and the signal-to-noise ratio (SNR) levels are set to 10 dB, 20 dB, and 40 dB. To show robustness of the utilized algorithm, it was run 50 times in MATLAB 2018a and the simulations were run on a machine with Windows 11 installed, a 2.40 GHz Intel processor, and 8 GB of RAM. In the second case study, the developed methodology is used to estimate the interharmonics of a grid connected PV system.

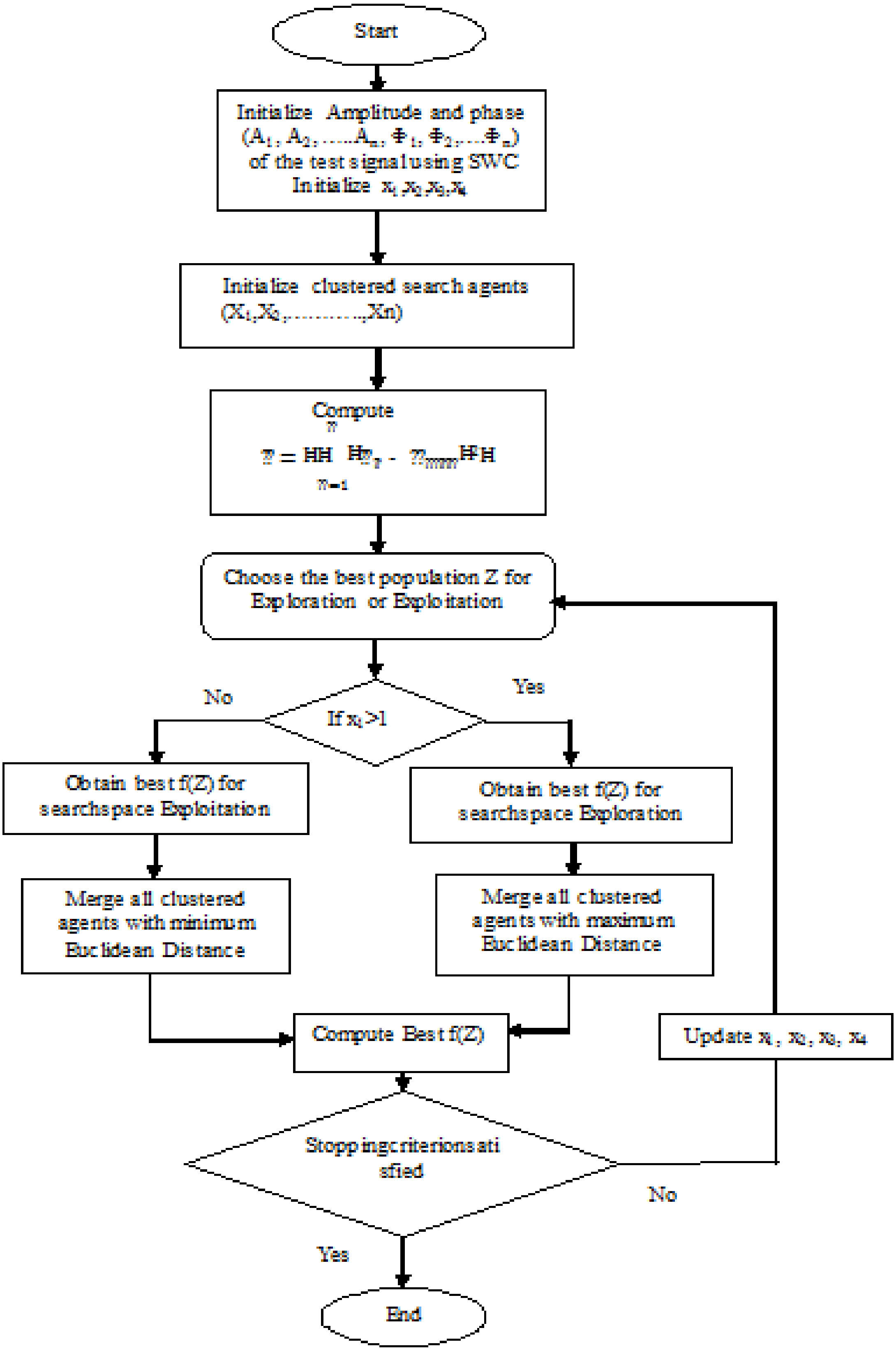

Figure 1: Flow diagram of the suggested hybrid SWC-MSCA interharmonic estimator

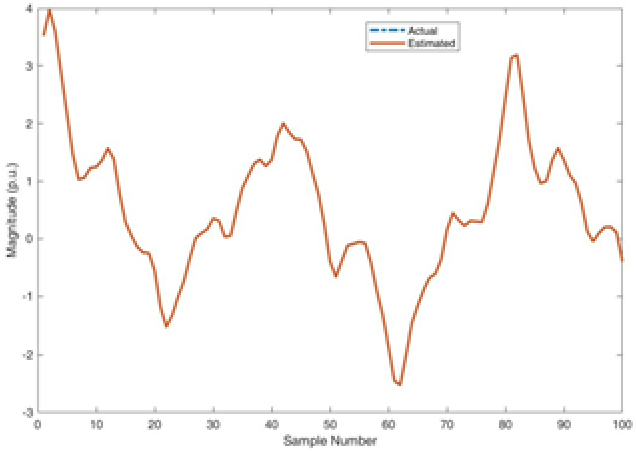

Figure 2: Actual signal and the estimated signal by SWC-MSCA method under non-noisy conditions

4.1 Case Study 1: Estimation of Interharmonics in a Test Signal

A test signal with random noise and decaying DC components has been used for the estimation, that contains fundamental, 3rd, 5th, 7th, and 11th order frequency components [21]. Power electronic converters and arc furnaces are examples of industrial loads that produce this type of signal.

$$\begin{aligned} u(t) &= A_{sub}\sin(2\pi f_{sub}t+\phi_{sub}) + A_1\sin(2\pi f1t+\phi_1) + A_3\sin(2\pi f_3t+\phi_3) + A_{int1}\sin(2\pi f_{int1}t+\phi_{int1}) \\ &+ A_{int2}\sin(2\pi f_{int2}t+\phi_{int2}) + A_5 sin(2\pi f_5t+\phi_5) + A_7\sin(2\pi f_7t+\phi_7) + A_{11}\sin(2\pi f_{11}t+\phi_{11}) \\ &+ v_{dc}e^{-}\beta dct + \gamma(t) \end{aligned} \tag{4.1}$$

where $\gamma(t)$ represents a white gaussian noise having a mean of zero and a variance of one. The signal was reconstructed using the results obtained using the suggested SWC-MSCA algorithm, and the estimated signal was then compared to the original signal. Figure 2 shows the plot of actual signal and the estimated signal by the proposed methodology and it is found that the estimated values of power harmonics, including sub and interharmonics, are in line with the original signal.

The estimation results obtained from the proposed SWC-MSCA methodology are listed Table 3. Based on the findings, it is clear that the proposed strategy produces more accurate results. For the purpose of comparison of the effectiveness of the algorithm, simulations of the hybrid algorithm are carried out with competent algorithms such as DE and PSO with the same hybrid methodology.

The algorithms are constructed and executed using a hybrid method using the SWC methodology, with a population size of 30 and a maximum iteration count of 1000, respectively. The performance of the strategies is evaluated using the performance index (ζ), which is defined by

$$\zeta = \frac{\sum_{n=1}^{N}(u_n - u_{n_{est}})^2}{\sum_{n=1}^{N}(u_n)^2}, \tag{4.2}$$

where,u_n denotes the actual harmonic signal and $u_{n_{est}}$ denotes the harmonic signal's estimated output as determined by the estimating technique. The convergence characteristics are illustrated in Figure 4. The performance index with the execution time is compared with competent methods, and the results are given in Table 1. It is obvious that the proposed approach performs better in terms of accuracy and computing time.

Table 1: Performance indexes and computational time of various techniques

Technique	**Performance Index**	**Time (s)**
SWC-PSO	0.0013	7.33
SWC-DE	7.635E-04	7.29
SWC-MSCA	**5.3736e-04**	**4.62**

For noisy scenarios, three signals are created by introducing noise to the original test signal with SNR values of 10 dB, 20 dB, and 40 dB respectively, and the suggested algorithm processes each signal individually. Figures 5-7 show

Techniques	Parameters	subharmonics	Fundamental harmonics	3rd harmonics	Inter harmonics I	Inter harmonics II	5th harmonics	7th harmonics	11th harmonics
ACTUAL	*f*	20	50	150	180	230	250	350	550
	A	0.505	1.50	0.50	0.25	0.35	0.20	0.15	0.10
	Ø	75	80	60	65	20	45	36	30
BFO-RLS [13]	A	0.5110	1.5029	0.4921	0.2581	0.3639	0.2009	0.1479	0.1015
	% error	1.1900	0.1952	1.5887	3.2372	3.9651	0.4541	1.4149	1.4800
	Ø	74.8100	79.9148	59.0760	65.3445	19.8677	46.2780	36.4473	30.0643
	% error	0.2530	0.1060	1.5400	0.5300	0.6610	2.8410	1.2430	0.2140
FA-RLS [17]	A	0.4990	1.4984	0.5004	0.2457	0.3497	0.2009	0.1497	0.0999
	% error	1.1881	0.1066	0.0800	1.7200	0.0857	0.4500	0.2000	0.1000
	Ø	74.9310	79.9480	59.5410	65.2030	19.9730	45.5230	36.1280	30.0126
	% error	0.0912	0.0642	0.7643	0.3125	0.1305	1.1642	0.3572	0.0421
BBO-RLS [18]	A	0.4943	1.4984	0.5003	0.2458	0.3497	0.2008	0.1485	0.0999
	% error	1.1255	0.1046	0.0785	1.6506	0.0788	0.4452	0.9557	0.1000
	Ø	74.9321	79.9500	59.5228	65.1706	19.9775	45.5200	36.1179	30.0123
	% error	0.0905	0.0625	0.7452	0.2625	0.1125	1.1565	0.3275	0.0410
GSA-RLS [19]	A	0.4940	1.4985	0.5002	0.2029	0.3497	0.2007	0.1497	0.0999
	% error	1.1065	0.0945	0.0553	1.4536	0.0658	0.3552	0.7556	0.0900
	Ø	74.9430	79.9588	59.6068	65.0146	19.9792	45.4974	36.1107	30.0097
	% error	0.0755	0.0515	0.6552	0.2255	0.1036	1.1055	0.3075	0.0326
MABC [6]	A	0.5052	1.5008	0.4998	0.2500	0.3500	0.1997	0.1500	0.1000
	% error	0.0468	0.0530	0.0441	0.0133	0.0011	0.1386	0.0319	0.0184
	Ø	74.9539	79.9800	60.1254	64.9374	20.0400	45.1636	35.9987	29.9580
	% error	0.0615	0.0250	0.2091	0.0964	0.2001	0.3636	0.0036	0.1401
SWC-MSCA	A	0.5049	1.4999	0.4998	0.2500	0.3500	0.1998	0.1500	0.1000
	% error	0.0198	0.0077	0.0400	0.0066	0.0029	0.0993	0.0220	0.0038
	Ø	75.0010	80.0010	60.0010	64.9998	20.0010	45.0010	36.0009	29.9991
	% error	0.0013	0.0013	0.0017	0.0003	0.0050	0.0022	0.0025	0.0030

Figure 3: Results for test signal with inter and sub-harmonics with techniques reported in literature and SWC-MSCA Method

the real vs estimated output utilizing the suggested SWC-MSCA algorithm with various noise levels. The estimated value nearly matches the actual value at 40 dB SNR, but when the SNR value of the signal declines, the predicted value deviates further from the actual value. Table 2 illustrates the performance indexes of various techniques at different SNR levels and are compared with the proposed methodology. The results show that the suggested SWC-MSCA hybrid approach based interharmonic estimator outperforms the other well-established algorithms in terms of both accuracy and computational time in all circumstances. The major goal of this new approach is to provide faster calculation and increased estimation accuracy.

4.2 Case study 2: Estimation of Interharmonics in a Grid Connected PV System

For the purpose of examining the interharmonics from PV systems connected to grid, a Matlab Simulink model has been developed for a 30-kW 3-ph grid-connected PV system with MPPT controller. The PV full-bridge inverter has a significant impact on controlling the transfer of power from the PV arrays to the grid. To extract the maximum power from the PV arrays, the perturb and observe (P&O) algorithm-based MPPT is used. A PI controller, is used to regulate

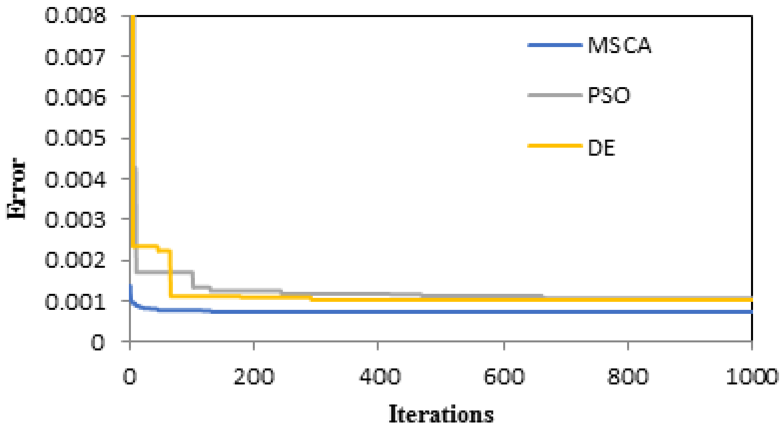

Figure 4: Convergence characteristics of the algorithms under non-noisy conditions

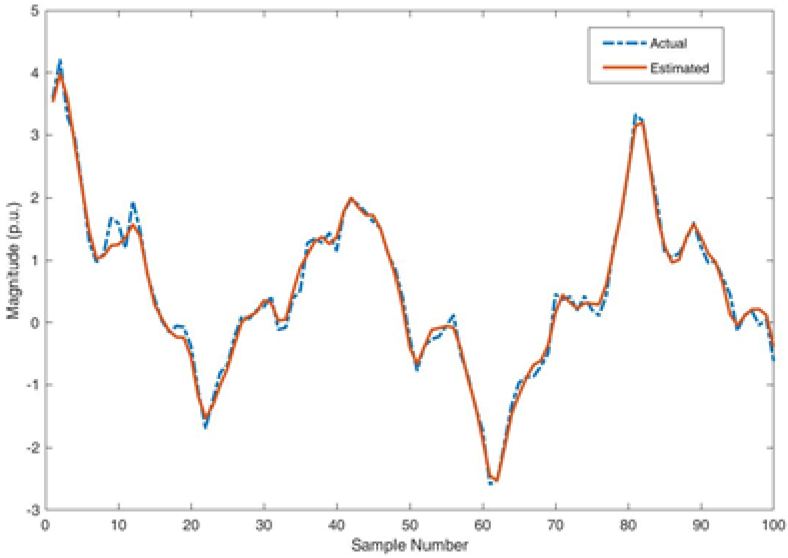

Figure 5: Actual signal and estimated signal by SWC-MSCA method with 10 dB SNR

the dc-link voltage vdc accordingly through the control of amplitude of the grid current , which is generated based on the phase of grid voltage that is derived from a phase-locked loop (PLL). The proposed SWC-MSCA methodology is employed for the estimation of interharmonics in the grid current. Figure 8 shows the spectrum of frequencies of grid current and interharmonics are observed at low-power operations due to the perturbation of MPPT.

5 Conclusion

Interharmonics estimation is the process of estimating the amplitude, phase, and frequency of the power system signal, which is necessary for designing filters to eliminate harmonic effects. In this paper a maiden attempt has been made for more accurate estimation of interharmonics using hybrid SWC-MSCA methodology. The first case study is carried out for the test signal consisting of inter and sub harmonic conditions, and the simulation results are compared with methods reported in literature in terms of accuracy, execution times, and performance indexes, for the purpose of demonstration of the strength of the proposed algorithm. The execution times and percentage errors acquired using the proposed estimation approach are fewer than those obtained using the other metaheuristic methods. The proposed algorithm is also used to estimate interharmonics in a three-phase low power PV system that is connected to the grid. As a future work, it is aimed to design the MPPT controller parameters using the results obtained from the suggested estimator.

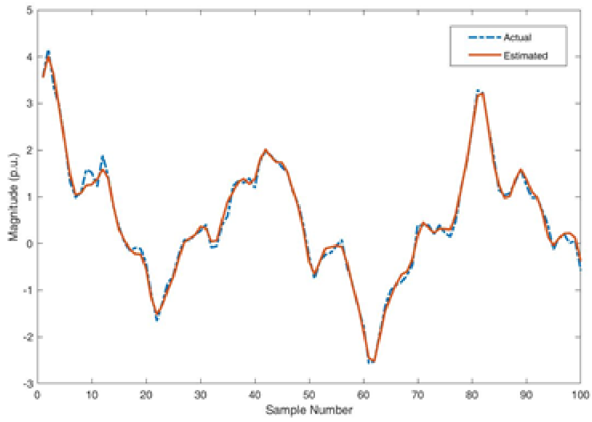

Figure 6: Actual signal and the estimated signal by SWC-MSCA method with 20 dB SNR

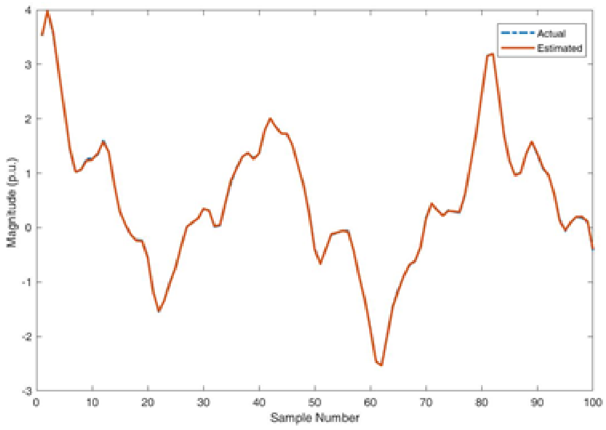

Figure 7: Actual signal and estimated signal by SWC-MSCA method with 40 dB SNR

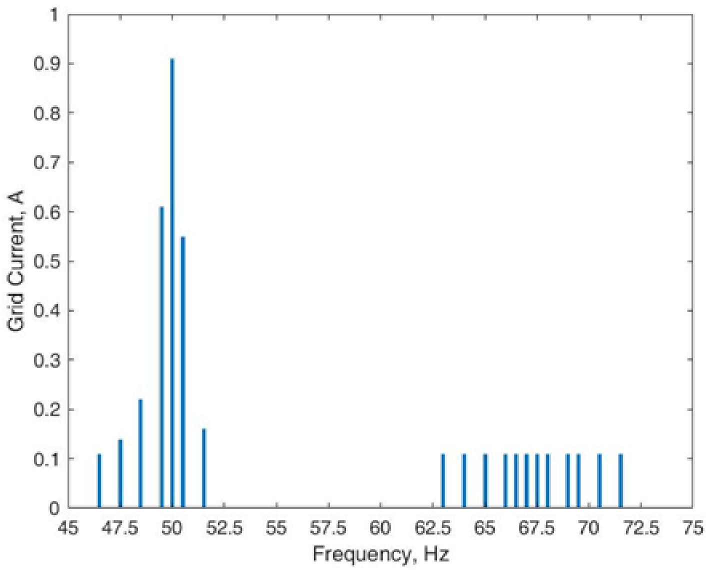

Figure 8: Grid current frequency spectrum during steady-state MPPT operation

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Table 2: Performance indexes of various techniques at different SNR levels

Techniques	SNR Values		
	10 dB	**20 dB**	**40 dB**
BFO-RLS [13]	4.548	0.787	0.092
FA-RLS [17]	3.974	0.561	0.078
BBO-RLS [18]	3.855	0.573	0.075
GSA-RLS [19]	3.652	0.547	0.065
MABC [6]	0.953	0.095	9.5353e-04
Proposed Method	**0.0014**	**0.0013**	**6.9103e-04**

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