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Distribution Harmonic State Estimation Based on a Hybrid PSO and SA Algorithm Considering Parameters Uncertainty

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Abstract: **This paper presents a new algorithm based on a Hybrid Particle Swarm Optimization (PSO) and Simulated Annealing (SA) called PSO-SA to estimate harmonic state variables in distribution networks. The proposed algorithm performs estimation for both amplitude and phase of each harmonic currents injection by minimizing the error between the measured values from Phasor Measurement Units (PMUs) and the values computed from the estimated parameters during the estimation process. The proposed algorithm can take into account the uncertainty of the harmonic pseudo measurement and the tolerance in the line impedances of the network as well as uncertainty of the Distributed Generators (DGs) such as Wind Turbines (WT). The main feature of proposed PSO-SA algorithm is to reach quickly around the global optimum by PSO with enabling a mutation function and then to find that optimum by SA searching algorithm. Simulation results on IEEE 34 bus radial and a realistic 70-bus radial test networks are presented to demonstrate the speed and accuracy of proposed Distribution Harmonic State Estimation (DHSE) algorithm is extremely effective and efficient in comparison with the conventional algorithms such as Weight Least Square (WLS), Genetic Algorithm (GA), original PSO and Honey Bees Mating Optimization (HBMO) algorithm.**

***Index Terms*--** **Harmonic State Estimation, Distributed Generators, Uncertainty Analysis, Particle Swarm Optimization, Simulated annealing, Distribution Networks.**

I. Introduction

In order to keep the modern grids under optimum cost as well as load forecasting, outage/restoration management, etc., Distribution State Estimation (DSE) is applied to answer such vital necessities. Employing innovative products and services, together with, intelligent monitoring, control, communication, and self-healing technologies, stimulate DSE and harmonic DSE implementation in modern electric systems. We believe the future will bring us more small distributed power generation units connected to the grid. The study and investigating of the grid integration of DGs lead researches in focusing on the rise of DGs' and the other loads' harmonic injection and the voltage quality of such distributions grids. In a deregulated electricity industry, new concerns have appeared regarding the quality of power supply as well as localization of the sources of power quality (PQ) disturbances. One of the main concerns regarding the quality of power supply is the harmonic pollution.

A previous step needed before the DHSE is identification whether or not sufficient measurements are available to perform the estimation. Because of very high number of elements, nodes and loads in distribution networks, it is needed many online measurements to provide full observability that are very expensive and non practical. However, (harmonic) pseudo measurements applications along with new algorithms help not only reducing the number of measurements but also maintaining the estimation error at a specific value.

Meliopoulos [1] utilized WLS approach to estimate harmonics amplitude in electrical network with synchronized measurement. The Kalman filtering approach has also been employed to estimate different states of integral harmonics in an electrical signal [2]. The authors [3] examine singular value decomposition (SVD) for the estimation of harmonics in electric network in the presence of high noise. Muscas et al. suggested a DHSE algorithm for under-determined distribution networks [4]. A method for estimating interharmonic frequencies in power system voltage and current signals based on a spectrum-estimation method known as "estimation of signal parameters via rotational invariance techniques" (ESPRIT) is proposed in [5]. a new two-stage, self-tuning least-squares (STLS) digital signal processing algorithm for PQ indices estimation according to the power components and PQ indices definitions given in the IEEE Std 1459–2010 is introduced in [6]. Moreover, Gursoy et al. offered complex Independent Component Analysis for harmonic source identification and estimation [7]. In addition, Carta proposed two measurement procedures based on a fixed and frequency dependent observation window for high performance Phasor Measurement Units (PMUs) [8]. In addition, a novel approach to the estimation of the harmonic sources by means of a Bayesian approach is proposed [9].

In recent years, heuristic techniques are attractive for very complicated optimization, high degree of variables and nonlinearity problems. These improved solutions offer two major advantages: "(1) development time is much shorter than when using more traditional approaches, and (2) the systems are very robust, being relatively insensitive to noisy and/or missing data" [10]. Due to the existence of distributed generation and nonlinear modeling of some distribution network elements, the conventional methods could not be

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easily used. To solve such problem, evolutionary methods and expert systems such as Neural Networks (NN), Genetic Algorithms (GA), Honey Bee Mating Optimization (HBMO), and Particle Swarm Optimization (PSO) can be utilized. A new algorithm is presented in [11] based on the Particle Swarm Optimizer with passive congregation (PSOPC) to estimate the phases of the harmonics, alongside a least square method that is used to estimate the amplitudes. A novel harmonic DSE based on HBMO algorithm whose speed and accuracy is better that some conventional DSE such as WLS [12]. In addition, an evolutionary strategy based on mutation and recombination processes has been developed for three-phase harmonic distortion state estimation algorithm [13]. In addition, techniques based on PSO are effective in nonlinear optimization problems, are not mainly affected by the size and nonlinearity of the problem, and can converge to the optimal solution in many problems where most analytical methods fail to converge [10].

Recently, a new optimization algorithm based on hybrid PSO and Simulated Annealing (SA) called PSO-SA has been used to solve difficult optimization problems such as comprehensive regression model and clustering and it was used on a number of different applications [14]-[16].

In this paper, a new algorithm based on a Hybrid PSO and Simulated Annealing (SA) called PSO-SA [14] is presented to estimate harmonic state variables for a practical distribution HSE including wind turbines (WTs) considering the uncertainty of network parameters, loads, WTs, and measurements. In this method, the harmonic currents (amplitude and phase) injections of WTs and loads are considered as the state variables in which the differences between measured and calculated values are assumed as the objective function.

II. Original PSO

Among the three types of constriction factors presented in [17], here, we applied the simple version (type$1''$) which requires the least number of adjusting parameters with no increase in time or memory resources.

The modification formula of constriction factor for the original PSO is as follows:

$$\begin{aligned} &V_i^{(k+1)} = \chi(V_i^{(k)} + c_1 \times rand_1 \times (Pbest_i - X_i^{(k)}) \\ &+ c_2 \times rand_2 \times (Gbest - X_i^{(k)})) \\ &X_i^{(k+1)} = X_i^{(k)} + V_i^{(k+1)} \end{aligned} \tag{1}$$

where

$V_i^{(k)}$: the velocity of *ith* particle at the iteration *k*;

$X_i^{(k)}$: the position of *ith* particle at the iteration *k*;

χ : the constriction factor;

$Pbest_i$: the best value of *ith* particle so far;

$Gbest$: the best value among the $Pbest_i$ s so far;

$rand$: a random variable between 0 and 1;

c_1 & c_2 : constants.

In order to control the particles' convergence, explosion and stability, constriction coefficient is calculated as [17]:

$$\chi = \begin{cases} \sqrt{\dfrac{2\kappa}{\varphi - 2 + \sqrt{\varphi^2 - 4\varphi}}} \;, & \varphi > 4 \\ \sqrt{\kappa} & else \end{cases} \tag{2}$$

$$\varphi = c_1 + c_2$$

The coefficient, $\kappa \in]0,1[$, controls the exploration versus the exploitation propensities. For bigger values of κ, the particles desire more exploration and prevent the explosion, i.e., they derive slow convergence and searching thoroughly the space before collapsing into a point. However, for smaller values of κ, the particles care more exploitation and less exploration [17].

To break through the stagnation of particles, mutation function was applied in the proposed PSO algorithm. The mutation function was executed when *Gbest* is not improving with the increasing of the number of iterations (for more details, refer to [18]). In this paper, if the *Gbest* after 20 iterations does not improving, mutation function with the mutation probability of 0.8 was applied.

III. Simulated Annealing

SA is an optimization technique that has been successfully used for solving a wide range of combinatorial optimization problems. The SA algorithm is an optimization procedure based on the behavior of condensed matter at low temperatures that mirrors the annealing process that takes place in nature. The procedure employs methods that originated from statistical mechanics to find global minima of systems with very large degrees of freedom [19]-[22].

It is common to most classes of meta-heuristics that are based on gradual ''local improvements'', including the SA algorithm, that the algorithm starts off with a non-optimal initial configuration (which may be chosen randomly) and proceeds to improve it by selecting a new configuration by using a suitable mechanism and calculating the corresponding cost differential ΔX_k. If the cost is reduced, then the new configuration is accepted and the process is repeated until a termination criterion is met.

Unfortunately, such methods can be easily trapped in local minima. The SA algorithm solves this problem by allowing ''uphill'' moves based on a model of the annealing process in the physical world as mentioned earlier. When metals slowly cool and anneal, their atoms are gradually ordered in a minimal energy state. During the cooling process the system can escape local minima by moving to a thermal equilibrium of a higher energy potential based on the probabilistic distribution *w* of entropy *S*, i.e.,

$$S = k \ln(w) \tag{3}$$

where *k* is the Boltzmann's constant and *w* is the probability that the system will exist in a state which relates to all the possible states that it could be in. Thus, given entropy's relation to energy E and temperature T, the reduction rate would be:

$$dS = \frac{dE}{T} \qquad (4)$$

which is actually the probabilistic expression of w related to the energy distribution of the temperature T as follows:

$$w \alpha \exp(-\frac{E}{kT}) \qquad (5)$$

The above formula is known as a Boltzmann probability distribution and is used to select the uphill moves that may help the optimization procedure escape from local minima.

The general procedure for the SA algorithm can be summarized as follows:

Step 1: Select an initial line configuration C and an initial temperature T.

Step 2: Find another solution, namely C_{next} by modifying the last answer C.

Step 3: Calculate the energy differential $\Delta E = f(C_{next}) - f(C)$

Step 4: If ΔE < 0; then go to Step 9.

Step 5: Generate a random number namely R between 0 and 1.0.

Step 6: If then, $R < \exp(-\frac{\Delta E}{T})$ go to Step 9.

Step 7: Repeat Steps 2–6 for a number of optimization steps for the given temperature.

Step 8: If no new configuration C_{next} is accepted, then go to Step 10.

Step 9: Decrease the temperature T, replace C with C_{next}, and go to Step 2.

Step 10: Reheat the environment by setting T to a higher value.

Step 11: Repeat Steps 1 through 10 until no further improvement is obtained.

IV. Proposed Algorithm Based on PSO-SA to DHSE

The HSE problem is an optimization problem with equality and inequality constraints. HSE including DGs can be expressed as follows:

A) Objective function:

$$\begin{aligned} &Min\ f(\overline{X}) = \sum_{i=1}^{m} \omega_i (z_i - h_i(\overline{X}))^2 \\ &\overline{X} = [\overline{AH}, \overline{PH}] \\ &\overline{AH} = [AH^1, AH^2, ..., AH^N] \\ &\overline{PH} = [PH^1, PH^2, ..., PH^N] \end{aligned} \qquad (6)$$

where: $\overline{X}$ is the state variables vector including the states' harmonics (amplitude and phase) injections. z_i is the measured values. ω_i is the weighting factor of the i^{th} measured variable. h_i is the state equation of the i^{th} measured variable. m is the number of measurements. N is the number of network states. The state variables are node harmonic currents' amplitude and phase.

B) Constraints

Constraints are defined as follows:

- Active power constraints of DGs:

$$P^i_{G,min} \le P^i_G \le P^i_{G,max} \qquad i = 1,2,3,...N_g \qquad (7)$$

- Distribution line limits:

$$\left|P^{Line}_{ij}\right| < P^{Line}_{ij,\max} \qquad (8)$$

- Harmonics:

$$AH_i^{\min} < AH_i < AH_i^{\max} \qquad i = 1, 2, ..., N \qquad (9)$$

$$PH_i^{\min} < PH_i < PH_i^{\max} \qquad i = 1, 2, ..., N \qquad (10)$$

- Tap of transformers:

$$Tap_i^{\min} < Tap_i < Tap_i^{\max} \qquad i = 1, 2, ..., N_t \qquad (11)$$

- Bus voltage magnitude

$$V_{\min} \le V_i \le V_{\max} \qquad i = 1,2,3, \dots, N_b \qquad (12)$$

- Active power constraints of loads:

$$P^i_{Load,min} \le P^i_{Load} \le P^i_{Load,max} \qquad i = 1,2,3,...N_L \qquad (13)$$

- Reactive power constraint of capacitors

$$0 \le {Q_c}^i \le Q^i_{c,max} \qquad i = 1,2,3,..., N_c \qquad (14)$$

Online measurements (PMUs) have been considered the harmonic currents (amplitude and phase) injections of loads and WTs or harmonic currents of lines. In this paper, average outputs and standard deviations (for fundamental and considered harmonics) of WTs and loads, which are variable, are considered as pseudo instrument devices. Moreover, all of electrical parameters are calculated based on [27]. The relationship between pseudo measurement error and SD is expressed in [23]. Since $\pm 3\sigma$ deviation about the mean covers more than 99.7% area of the Gaussian curve, the standard deviation of real or pseudo measurement was computed as follows in a Gaussian distribution:

$$\sigma_i = \frac{\mu_i \times error_i\%}{3 \times 100} \qquad (15)$$

where μ_i is the true (or mean) value of the *ith* real (or pseudo) measurement and $error_i\%$ is the error in percent of that real (or pseudo).

Harmonic load flow is implemented by the direct solution presented in [24] by building the bus-injection to branch-current (BIBC) and branch-current to bus-voltage (BCBV) matrices which is modified for harmonic load flow. The load flow error employed for convergence check is maximum deviation of voltage buses in sequential iterations.

In this work, an algorithm based on a PSO-SA proposed to DHSE. To apply the PSO-SA to solve DHSE problem, the following steps have to be applied:

Step 1: Define the input data from PMUs and the network line parameters, topology, pseudo measurements and errors.

Step 2: Generate the initial population

Step 3: Find $\boldsymbol{P_{best}}$ and $\boldsymbol{G_{best}}$ by PSO algorithm using constriction factor.

Step 4: If objective function value at $\boldsymbol{G_{best}}$ < predefined constant, continue, otherwise go to **Step 6**.

Step 5: Apply **SA** to search around the $\boldsymbol{G_{best}}$ solution and go to **Step 9**.

Step 6: Update the position and velocity of the primary PSO particles.

Step 7: Apply the ***mutation function***.

Step 8: If the termination criteria satisfy, continue otherwise go to **Step 3**.

Step 9: End.

The termination criterion is the estimation error that can be set from 1e-3 to 1e-6. The flowchart of proposed PSO-SA to DHSE is shown in Fig. 1.

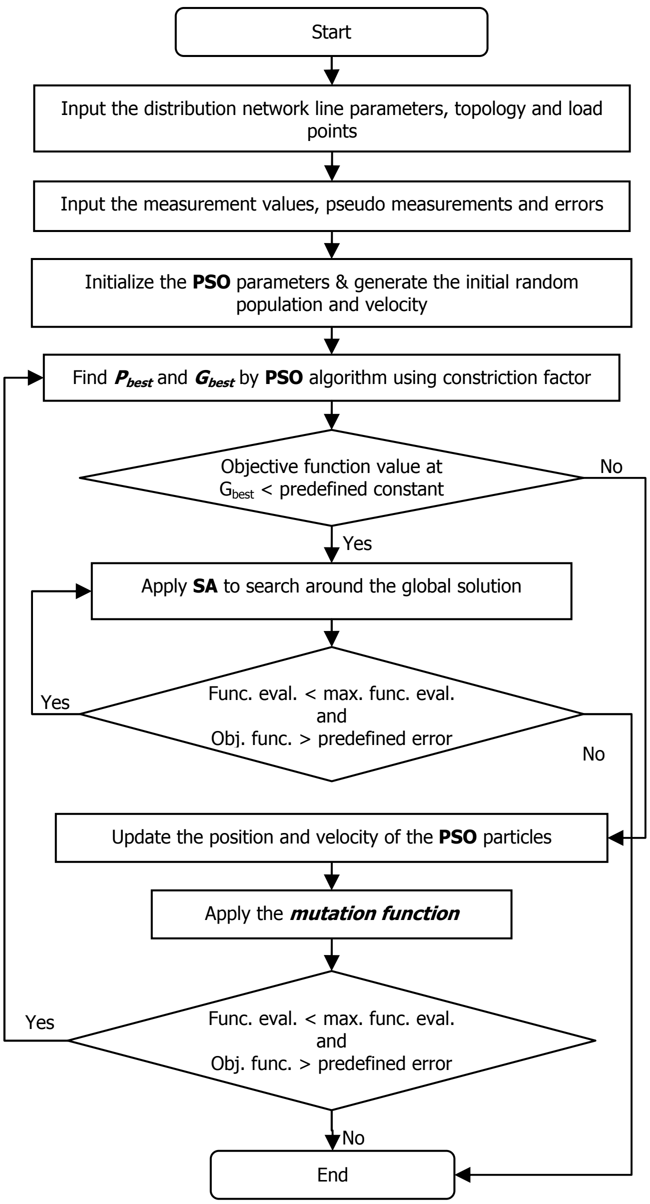

Fig.1. flowchart of proposed PSO-SA to DHSE

V. Uncertainty Analysis

It is obvious the uncertainties affect the measures and setting parameters and make the results of SE algorithm uncertain. To evaluate the performance of proposed DHSE algorithm based on PSO-SA, Monte Carlo simulation was performed [4]. The uncertainty of the harmonic pseudo measurement, the accuracy of the PMUs and the tolerance in the line impedances of the network as well as uncertainty of the WT are into account. In order to consider such uncertainties, first, 50 references of network states are derived by applying the uncertainties the loads and WTs outputs which are generated randomly from the Gaussian distribution function. In the next step, the other uncertainties such as measurement accuracy and network parameters uncertainty will be applied. The number of Monte Carlo iterations for each condition of network is 100. An each iterations of Monte Carlo, the measured data corrupted and DHSE algorithm is applied by using this data to estimate the states. The results obtained from 100 run of Monte Carlo are processed to assess the uncertainty of the DHSE.

VI. Simulation results

proposed algorithm is applied to DHSE on two distribution test systems:

Case 1: IEEE 34 bus radial test feeder: including 3 WTs.

Case 2: a 70-bus radial test network: including 6 WTs.

It is assumed that the following information is available:

- Standard deviations of injected harmonics for loads and WTs, measurement accuracy and tolerance of parameters.
- Values of PMUs
- Set points of VRs and local capacitors

In this paper, the harmonic currents (amplitude and phase) injections of WTs and loads are considered as the state variables. Moreover, the PMUs are multichannel instruments. In following, some results of case 1 are presented.

Case 1: IEEE 34 bus radial test feeder

Fig. 2. shows the IEEE 34 bus radial distribution test feeders whose associated specifications are presented in [25].

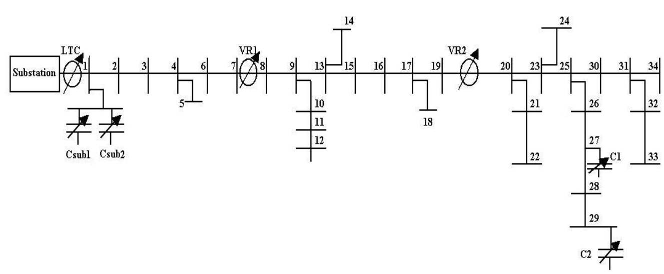

Fig.2. Single line diagram of IEEE 34-bus test system

For this system, it is assumed that there are three WTs connected at buses 6, 17 and 29, whose specifications are presented in Table I. There are also 6 variable loads whose specifications are demonstrated in Table II.

TABLE I
CHARACTERISTIC OF GENERATORS

	WT1	WT2	WT3
Average of active power output (kW)	60	80	90
Standard deviation (%)	25	15	15
Power factor	0.8	0.8	0.8

TABLE II
CHARACTERISTIC OF VARIABLE LOADS

Location	Active power (phase a) (kW)	Reactive power (phase a) (KVar)	Active power (phase b) (kW)	Reactive power (phase b) (KVar)	Active power (phase c) (kW)	Reactive power (phase c) (KVar)	Standard Deviation (%)
2	0	0	32	16.5	26	14	20
10	34	18	0	0	0	0	15
13	0	0	42	22	0	0	10
22	27	22	27	22	27	22	20
27	134	107	134	107	134	107	10
30	20	16	20	16	62	38	20

The loads at buses 22 and 30 and WTs are nonlinear loads and inject harmonics to network. In addition, there are three PMUs available on buses 4, 13 and 25. The harmonic specifications are presented in Table III.

TABLE III
HARMONIC CHARACTERISTICS OF NONLINEAR LOADS (%)

Load Bus No.	5^{th} (250 Hz)	7^{th} (350 Hz)	11^{th} (550 Hz)	13^{th} (650 Hz)	Standard deviation (%)
22	28	16	10	5	20
30	10	6	0	0	20
WTs	3	2	1	1	20

Tables IV and V show the estimated harmonics amplitudes and phase of for the load at bus 22 by proposed PSO-SA, HBMO, WLS, GA, and original PSO. Also, the l^2-norm of errors is reported. The results shown the individual error at each harmonic order as well as total error of estimation has been reduced by applying the proposed PSO-SA algorithm.

TABLE IV
COMPARISON OF THE ESTIMATED AMPLITUDES OF HARMINICS FOR THE LOAD AT BUS 22 BY PROPOSED PSO-SA, HBMO, WLS, GA, AND ORIGINAL PSO

Harmonic order	Amplitude (P.U.)	mean of estimated amplitude (P.U.)				
		PSO-SA	HBMO	WLS	GA	org. PSO
Fund. (50 Hz)	1.00	0.992	0.96	1.02	0.978	1.04
5^{th} (250 Hz)	0.28	0.283	0.275	0.23	0.225	0.261
7^{th} (350 Hz)	0.16	0.171	0.22	0.222	0.175	0.11
11^{th} (550 Hz)	0.10	0.11	0.081	0.145	0.044	0.139
13^{th} (650 Hz)	0.05	0.04	0.041	0.07	0.024	0.046
error (%)	-------	**1.88**	**7.12**	**9.06**	**8.22**	**7.33**

TABLE V
COMPARISON OF THE ESTIMATED AMPLITUDES OF HARMINICS FOR THE LOAD AT BUS 22 BY PROPOSED PSO-SA, HBMO, WLS, GA, AND ORIGINAL PSO

Harmonic order	Phase (degree)	mean of estimated phase (degree)				
		PSO-SA	HBMO	WLS	GA	org. PSO
Fund. (50 Hz)	-25	-24.8	-22.1	-33.9	-24.0	-25.4
5^{th} (250 Hz)	75	76.4	81.3	65.0	86.2	69.3
7^{th} (350 Hz)	-165	-162.7	-152.8	-171.4	-148.0	-164.5
11^{th} (550 Hz)	-65	-74.1	-51.4	-42.3	-73.1	-68.1
13^{th} (650 Hz)	-105	-99.4	-121.8	-85.3	-125.3	-119.8
error (%)	-------	**4.99**	11.67	15.19	13.54	7.33

Table VI shows the simulation results for the Maximum Individual Relative Error (MIRE):

$$MIRE(\%) = \max(|X_{est}(i) - X_{true}(i)| / |X_{true}(i)|) \times 100 \qquad (16)$$

In addition, Table VII presents the number of function evaluations to solve the problem.

TABLE VI
COMPARISON OF MIRE FOR ESTIMATED VALUES

		PSO-SA	HBMO	WLS	GA	orig. PSO
MIRE (%)	Amplitude	20	38	45	56	39
	Phase	14	21	36	19	14

TABLE VII
COMPARISON OF NUMBER OF FUNCTION EVALUATIONS

Method	PSO-SA	HBMO	WLS	GA	orig. PSO
NUMBER OF Function EVALUATIONS	405	560	790	970	650

Moreover, Monte Carlo simulations showed that the mean of estimated amplitudes and phases of harmonic currents lies within the bounds obtained from 95% confidence interval for the DHSE based on PSO-SA while other algorithm could not lie within those bounds for all states perfectly. The tolerance of line parameters is considered 20%.

Case 2: A realistic 70-bus test network

Fig. 3. shows the 70-bus test feeders whose associated specifications are presented in [26]. For this system, it is assumed that there are eight WTs and DGs whose parameters are presented in Table VIII. There are also 8 variable loads whose specifications are demonstrated in Table IX.

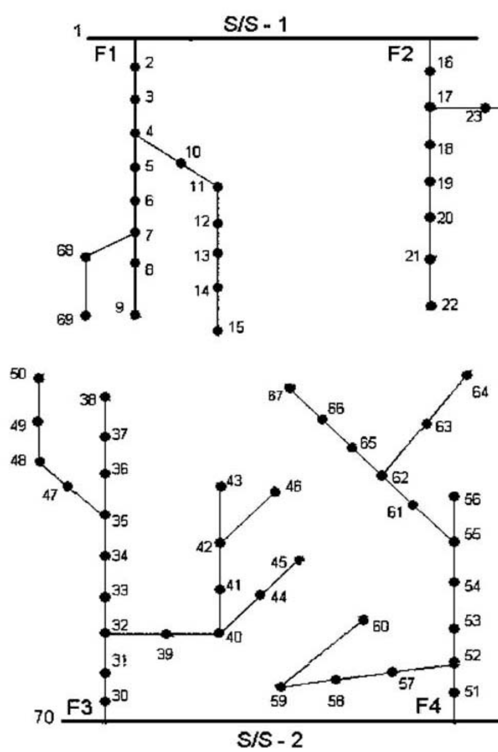

Fig. 3. Single Line Diagram of 70 bus test network

TABLE VIII
CHARACTERISTIC OF GENERATORS

	Average of active power output (kW)	Standard deviation (%)	location	Power factor
WT1	300	10	8	1
WT2	450	15	14	1
DG3	500	10	21	1
DG4	350	15	29	1
WT5	650	15	35	1
WT6	500	10	41	1
WT7	200	15	62	1
DG8	300	20	58	1

TABLE IX
CHARACTERISTIC OF VARIABLE LOADS

Location	Active power (kW)	Reactive power (KVar)	Standard deviation (%)
4	100	30	20
14	320	230	15
26	210	134	15
21	150	86	10
34	260	134	20
42	170	93	10
53	230	134	15
64	400	183	20

The loads at buses 4, 14 and 42 as well as five WTs are nonlinear loads and inject harmonics to network. The harmonic specifications are presented in Table X. In addition, six multichannel PMUs are available on buses 1, 70, 7, 17, 52 and 40.

Tables XI and XII show the estimated amplitudes and phase of harmonics for the load at bus 22 byproposed PSO-SA, HBMO, WLS, GA, and original PSO. The l^2-norm criterion has applied for total error. The results shown the individual error at each harmonic order as well as total error of estimation has been reduced by applying the proposed PSO-SA algorithm.

Tables XIII shows the simulation results for the MIRE(%). Also, Tables XIV presents the number of function evaluations to solve the problem.

TABLE X
HARMONIC CHARACTERISTICS OF NONLINEAR LOADS (%)

LOAD BUS NO.	5^{th} (250 Hz)	7^{th} (350 Hz)	11^{th} (550 Hz)	13^{th} (650 Hz)	STANDARD DEVIATION (%)
4	28	16	10	5	20
14	10	6	0	0	15
42	15	10	5	0	10
WTs	3	2	1	1	20

TABLE XI
COMPARISON OF THE ESTIMATED AMPLITUDES OF HARMINICS FOR THE LOAD AT BUS 4 BY PROPOSED PSO-SA, HBMO, WLS, GA, AND ORIGINAL PSO

Harmonic order	Amplitude (P.U.)	mean of estimated amplitude (P.U.)				
		PSO-SA	HBMO	WLS	GA	org. PSO
Fund. (50 Hz)	1.00	0.993	0.961	1.08	0.985	1.06
5^{th} (250 Hz)	0.28	0.286	0.236	0.19	0.38	0.273
7^{th} (350 Hz)	0.16	0.175	0.25	0.214	0.198	0.1
11^{th} (550 Hz)	0.10	0.13	0.068	0.141	0.044	0.147
13^{th} (650 Hz)	0.05	0.03	0.019	0.071	0.078	0.041
error (%)	-------	**3.80**	**11.01**	**13.23**	**11.82**	**9.24**

TABLE XII
COMPARISON OF THE ESTIMATED AMPLITUDES OF HARMINICS FOR THE LOAD AT BUS 4 BY PROPOSED PSO-SA, HBMO, WLS, GA, AND ORIGINAL PSO

Harmonic order	Phase (degree)	mean of estimated phase (degree)				
		PSO-SA	HBMO	WLS	GA	org. PSO
Fund. (50 Hz)	-25	-24.5	-21.3	-35.4	-23.2	-25.9
5^{th} (250 Hz)	75	76.2	81.1	64.1	83.1	68.2
7^{th} (350 Hz)	-165	-162.4	-150.0	-177.8	-147.1	-171.5
11^{th} (550 Hz)	-65	-74.2	-51.1	-42.7	-75.9	-68.6
13^{th} (650 Hz)	-105	-99.8	-122.1	-84.3	-128.7	-125.2
error (%)	-------	**4.97**	**12.50**	**16.44**	**14.82**	**10.23**

TABLE XIII
COMPARISON OF MIRE FOR ESTIMATED VALUES

		PSO-SA	HBMO	WLS	GA	orig. PSO
MIRE (%)	Amplitude	40	62	42	56	47
	Phase	14	21	42	23	19

TABLE XIV
COMPARISON OF NUMBER OF FUNCTION EVALUATIONS

Method	PSO-SA	HBMO	WLS	GA	orig. PSO
NUMBER OF Function EVALUATIONS	780	1350	1870	2300	1240

Moreover, Monte Carlo simulations with 20% deviation in line parameters showed that the mean of estimated amplitudes and phases of harmonic currents lies within the bounds obtained from 95% confidence interval for the DHSE based on PSO-SA while other algorithm could not lie within those bounds for all states perfectly.

VII. CONCLUSION

The results of simulations showed that the DHSE algorithm based on proposed PSO-SA is successful to find the global optimum and is very precise. In other words, this method not only reaches to the better optimal solution as compared to other methods, but also has small standard deviation in different trials. The proposed algorithm is robust that can perform the DHSE even in presence of uncertainty in harmonic pseudo measurement, the accuracy of the measurement and the tolerance in the line impedances of the network as well as uncertainty of WTs outputs.

In regards to expense of computation, the number of function evaluations, and errors for estimated values, proposed PSO-SA shows excellent performance as compared to WLS, GA, HBMO and original PSO. These results lead us to conclude that the proposed PSO-SA algorithm is truly efficient, effective, and robust to reach optimum solutions for practical and complex DHSE problems. Moreover, Monte Carlo simulations with 20% deviation in line parameters and other uncertainties mentioned in simulations showed that the mean of estimated amplitudes and phases of harmonic currents lies within the bounds obtained from 95% confidence interval for the DHSE based on PSO-SA while other algorithm could not lie within those bounds for all states perfectly.

VIII. References

[1] A. P. Sakis Meliopoulos, Fan Zhang, "Power System Harmonic State Estimation" IEEE Transaction on Power Delivery, Vol. 9, pp.1701-1709, July 1994.

[2] K.K.C., Yu, N. R., Watson, J. Arrillaga, "An adaptive Kalman filter for dynamic harmonic state estimation and harmonic injection tracking," Power Delivery, IEEE Transactions on , vol.20, no.2, pp. 1577- 1584, April 2005.

[3] T. Lobos, T. Kozina and H.-J.Koglin, "Power System Harmonics Estimation Using Linear Least Squares Method And SVD", IEE Proceeding of Generation, Transmission and Distribution, Vol. 148, No. 6. November 2001.

[4] C. Muscas, F. Pilo, G. Pisano, S. Sulis, "Optimal Number And Location Of Measurement Instruments in Distributed Systems for Harmonic State Estimation", Electrical Power Quality and Utilisation, Vol. XIII, No. 1, pp. 75-81, 2007.

[5] Irene Yu-Hua Gu, and Math H. J. Bollen, "Estimating Interharmonics by Using Sliding-Window ESPRIT", IEEE Transactions on Power Delivery, Vol. 23, No. 1, Pages:13-23, January 2008.

[6] Vladimir V. Terzija and Vladimir Stanojevic, "STLS Algorithm for Power-Quality Indices Estimation", IEEE Transactions on Power Delivery, Vol. 23, No. 2, Pages: 544-552, April 2008.

[7] E. Gursoy, D. Niebur, "Harmonic Load Identification Using Complex Independent Component Analysis," Power Delivery, IEEE Transactions on , vol.24, no.1, pp.285-292, Jan. 2009.

[8] A. Carta, N. Locci, C. Muscas, "GPS-Based System for the Measurement of Synchronized Harmonic Phasors," Instrumentation and Measurement, IEEE Transactions on , vol.58, no.3, pp.586-593, March 2009.

[9] G. D'Antona, C. Muscas, S. Sulis, "State Estimation for the Localization of Harmonic Sources in Electric Distribution Systems," Instrumentation and Measurement, IEEE Transactions on , vol.58, no.5, pp.1462-1470, May 2009

[10] K. Y. Lee, M. A. El-Sharkawi, "Modern Heuristic Optimization Techniques, Theory and Applications to Power Systems", IEEE Press, ISBN 978-0471-45711-4, 2008.

[11] Z. Lu, T. Y. Ji, W. H. Tang and Q. H. Wu, "Optimal Harmonic Estimation Using A Particle Swarm Optimizer", IEEE Transactions on Power Delivery, Vol. 23, No. 2, Pages: 1166-1174, April 2008.

[12] A. Arefi, M.R. Haghifam, S.H. Fathi, T. Niknam, J. Olamaei, "A novel algorithm based on Honey Bee Mating Optimization for distribution harmonic state estimation including distributed generators", PowerTech, 2009 IEEE Bucharest, Page(s): 1 – 7, 2009.

[13] de Arruda, E.F.; Kagan, N.; Ribeiro, P.F.; , "Harmonic Distortion State Estimation Using an Evolutionary Strategy," Power Delivery, IEEE Transactions on , vol.25, no.2, pp.831-842, April 2010

[14] T. Niknam, B. Amiri, J. Olamaei, A. Arefi, "An efficient hybrid evolutionary optimization algorithm based on PSO and SA for clustering", Journal of Zhejiang University SCIENCE A, ISSN 1673-565X (Print); ISSN 1862-1775 (Online), Vol. 10, No. 4, 2009.

[15] Sun Qiu-gao; , "Mixed-Model Assembly Line Balancing Based on PSO-SA Alternate Algorithm," Intelligent Computation Technology and Automation (ICICTA), 2010 International Conference on , vol.2, no., pp.687-690, 11-12 May 2010.

[16] J. Behnamian, S. M. T. Fatemi Ghomi, "Development of a PSO-SA hybrid metaheuristic for a new comprehensive regression model to time-series forecasting", An International Journal of Expert Systems with Applications, Vol. 37, Issu. 2, March, 2010.

[17] M. Clerc, J. Kennedy, "The Particle Swarm—Explosion, Stability, and Convergence in a Multidimensional Complex Space", IEEE Transactions on Evolutionary Computation, Vol. 6, No. 1, Pages: 58-73, February 2002.

[18] A. Ratnaweera, S. K. Halgamuge, H. C. Watson, "Self-Organizing Hierarchical Particle Swarm Optimizer With Time-Varying Acceleration Coefficients", IEEE Transactions On Evolutionary Computation, Vol. 8, No. 3, Pages: 240-255 , June 2004.

[19] T. H. Wu, C. C. Chang, S. H. Chung, "A simulated annealing algorithm for manufacturing cell formation problems", Expert Systems with Applications, vol.34, no. 3, pp. 1609-1617, 2008.

[20] K., Meer, "Simulated Annealing versus Metropolis for a TSP instance. Information Processing Letters", vol. 104, no.6, pp. 216-2192007.

[21] A. Y. Saber, T. Senjyu, A. Yona, N. Urasaki, T. Funabashi, "Fuzzy unit commitment solution—A novel twofold simulated annealing approach", Electric Power Systems Research, 77(12), 1699-1712, 2007.

[22] Christober Asir Rajan. C and Mohan. M. R,. An evolutionary programming based simulated annealing method for solving the unit commitment problem, International Journal of Electrical Power & Energy Systems, 29(7), 540-550, 2007.

[23] R. Singh, B.C. Pal, R.A. Jabr, "Distribution System State Estimation through Gaussian Mixture Model of the Load as Pseudo-Measurement', IET Gener. Transm. Distrib., Vol. 4, Iss. 1, pp. 50–59, 2010.

[24] W.-M. Lin, J.-H. Teng, "Distribution fast decoupled state estimation by measurement pairing", IEE Proc.-Gener. Tuansm. Distrib., Vol. 143, No. 1 , Pages: 43-48, January 1996.

[25] W. H. Kersting, "Radial distribution test feeders", IEEE Transaction on Power System, Vol. 6, Issue 3, Pages: 975 - 985, Aug. 1991.

[26] D. Debaprya, "A fuzzy multi-objective approach for network reconfiguration of distribution systems", IEEE Transaction of Power Delivery, Vol. 21, Issue 1, Pages: 202-209, 2006.

Standards:

[27] "IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions," IEEE Std 1459-2010 (Revision of IEEE Std 1459-2000) , vol., no., pp.1-40, March 19 2010