Distribution Harmonic State Estimation Based on a Modified PSO Considering Parameters Uncertainty

A. Arefi, *Graduate Student Member, IEEE*, M. R. Haghifam, *Senior Member, IEEE*, S. H. Fathi, *Member, IEEE*

Abstract: **This paper presents a new algorithm based on a Modified Particle Swarm Optimization (MPSO) to estimate the harmonic state variables in a distribution networks. The proposed algorithm performs the estimation for both amplitude and phase of each injection harmonic currents 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 the uncertainty of the Distributed Generators (DGs) such as Wind Turbines (WTs). The main features of the proposed MPSO algorithm are usage of a primary and secondary PSO loop and applying the mutation function. The simulation results on 34-bus IEEE radial and a 70-bus realistic radial test networks are presented. The results demonstrate that the speed and the accuracy of the proposed Distribution Harmonic State Estimation (DHSE) algorithm are very excellent compared to the algorithms such as Weight Least Square (WLS), Genetic Algorithm (GA), original PSO, and Honey Bees Mating Optimization (HBMO).**

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

I. Introduction

A. Distribution Harmonic State Estimation (DHSE)

In order to keep the modern grids in optimum cost as well as load forecasting, outage/restoration management, etc., Distribution State Estimation (DSE) is applied to answer such necessities. Employing the innovative products and services together with the intelligent monitoring, control, self-healing, and communication technologies stimulates the DSE and Distribution Harmonic State Estimation (DHSE) implementation in modern electric systems. We believe the future will bring us more distributed small power generation units connected to the grid. The study and investigating of the grid integration of Distribution Generations (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 the power supply as well as localization of the sources of the power quality (PQ) disturbances. One of the main concerns concerning the quality of a power supply is the harmonic pollution.

Ali Arefi is with the Department of Electrical and Computer Engineering, Tarbiat Modares University, Tehran, Iran (e-mail: a.arefi@modares.ac.ir).

Mahmood-Reza Haghifam is with the Department of Electrical and Computer Engineering, Tarbiat Modares University, Tehran, Iran (e-mail: haghifam@modares.ac.ir).

Seyed Hamid Fathi is with the Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran (e-mail: fathi@aut.ac.ir).

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, many online measurements are necessary to provide full observability. Since this approach is very expensive and non-practical, (harmonic) pseudo measurements along with new algorithms are applied not only to reduce the number of measurements but also to maintain the estimation error at a specific value.

Meliopoulos [1] utilized WLS approach to estimate the harmonics amplitude in an electrical network with synchronized measurement. The Kalman filtering approach has also been employed to estimate different states of the integral harmonics in an electrical signal [2]. Lobos et al. examined singular value decomposition (SVD) for the estimation of harmonics in an electric network in the presence of high noise [3]. A method for estimating interharmonic frequencies of the voltage and the current signals based on a spectrum-estimation method known as "estimation of signal parameters via rotational invariance techniques" (ESPRIT) is proposed in [4]. A new two-stage, self-tuning least-squares (STLS) digital signal processing algorithm for the PQ indices estimation according to the IEEE Std 1459–2000 introduced in [5]. In addition, a novel approach to the estimation of the harmonic sources by means of a Bayesian approach has been proposed [6].

In recent years, the heuristic techniques are attractive for very complicated optimization, the high degree of variables, and the 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" [7]. Due to the existence of the DG and the nonlinear modeling of some distribution network elements, the conventional methods could not be easily used. To solve such problem, the evolutionary methods and the 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 [8] 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 DHSE based on HBMO whose speed and accuracy is better than some conventional algorithms is presented in [9]. In addition, an evolutionary strategy has been developed for three-phase DHSE algorithm [10]. In addition, techniques based on the PSO are effective in nonlinear optimization problems because the PSO 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 [7].

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In this paper, Due to the nonlinear and the discrete elements (tap changer, VRs etc.) as well as the presence of some uncertainties in the distribution networks, a new algorithm based on a Modified PSO (MPSO) is proposed for a practical DHSE including wind turbines (WTs). The proposed algorithm considers the uncertainty of the network parameters, the variations of the loads as well as the WTs, and the accuracy of the measurements. The main features of proposed MPSO algorithm are usage of a primary PSO loop, a secondary PSO loop, and applying the mutation function.

B. Paper Organization

In section II, the proposed Modified PSO algorithm is developed. In section III, the DHSE algorithm including DGs is presented. Section IV introduces the application of MPSO to DHSE. Section V presents the uncertainty analysis approach. Section VI analyzes the results from two case studies. Finally, Section VII provides some conclusions.

II. Modified PSO Algorithm

In this section, the proposed MPSO is presented. The main features of proposed MPSO algorithm are usage of two PSO-based optimization loop as well as applying the mutation function.

A. Original PSO

Comparing between two PSO using an inertia weight and using a constriction factor, the best approach is to use the constriction factor [11]. Therefore, in this paper, PSO using a constriction factor is applied. Three model of constriction factor is presented in [12], but simple version (Type $1''$) is selected here, because this type requires the least number of adjusting coefficients with no increase in time or memory resources [12].

The modification formulas of a constriction factor for the original PSO is as (1) and the related searching method schema is shown in Fig. 1.

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

where

$V_i^{(k)}$: velocity of *i-th* particle at time *k*;

$X_i^{(k)}$: position of *i-th* particle at time *k*;

χ : constriction factor;

$Pbest_i$: the best value of *i-th* particle so far;

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

$rand$: random Variable between 0 and 1;

c_1 & c_2 : constants.

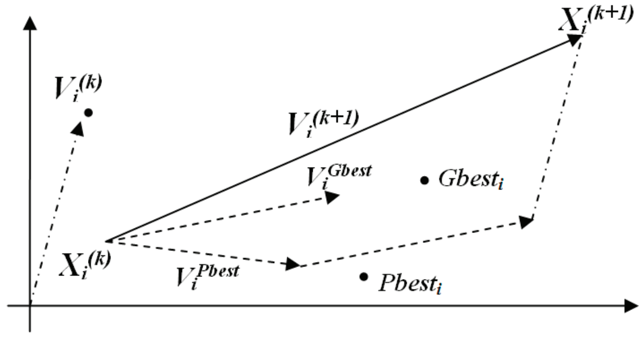

Fig. 1: Searching method schema of the constriction factor-based PSO

In order to control the system's convergence, explosion, and stability of the PSO, the constriction coefficient (χ) is calculated from (2) as:

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

$$\varphi = c_1 + c_2$$

In (2), $\kappa \in]0,1[$ is a coefficient allows control of exploration versus exploitation propensities. For bigger value of coefficient κ, particles desire more exploration and preventing explosion, derives slow convergence and searching thoroughly the space before collapsing into a point. However, for smaller values, particles care more exploitation and less exploration [12].

B. Secondary PSO loop

In order to achieve a better performance and speed in the convergence, a secondary optimization loop based on PSO [13] is utilized. The secondary PSO as an inner loop is applied when the objective function value of $Gbest$ in primary PSO is less than a predefined constant. This constant can be 0.0001, 0.001, or 0.01 regarding to the overall accuracy and the objective function complexity. In the secondary PSO, the particle population, the coefficient κ, and the particles' position limit (the range) is less than those values in the primary PSO. In the secondary PSO, the new particle population does not generated, however, the particles were selected among the primary PSO's particles that have better objective function value. Because the PSO with the lower κ tends to the local searching and performs a quick convergence, the overall number of the objective function evaluation will be reduced.

C. Mutation function

It is shown that the PSO algorithm can find quickly a good solution, however it often remains around such solution for a great number of iterations without any considerable improvement. Therefore, in order to control such behavior and break through the stagnation of particles, a mutation function was applied in the proposed MPSO algorithm [14]. The mutation function is conceptually equivalent to the mutation in genetic algorithms. The mutation function was executed when $Gbest$ is not improving while the increasing of the number of iterations. The mutation function selects a particle randomly and then adds a random perturbation to a randomly selected modulus of the velocity vector of that particle by a mutation probability.

In this paper, if the *Gbest* after 20 iterations does not improving, the mutation function with the mutation probability of 0.7 will be applied.

III. DHSE Including DG

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

A. Objective function:

$$Min\ \ f(\overline{X}) = \sum_{i=1}^{m} \omega_i (z_i - h_i(\overline{X}))^2$$
$$\overline{X} = [\overline{AH}, \overline{PH}] \tag{3}$$
$$\overline{AH} = [AH^1, AH^2, ..., AH^N]$$
$$\overline{PH} = [PH^1, PH^2, ..., PH^N]$$

where

$\overline{X}$: the state variables (harmonics injections) vector;

AH^i : the amplitude of the i^{th} state variable;

PH^i : the phase of the i^{th} state variable;

z_i: the i^{th} measured value;

ω_i: the weighting factor of the i^{th} measured variable;

h_i: the state equation of the i^{th} measured variable;

m: the number of measurements;

N: the number of network states.

The state variables are considered both amplitude and phase of injection harmonic currents in this paper.

B. Constraints

The limits of active power of DGs and loads, bus voltage magnitude, amplitude and phase of harmonic currents, reactive power of capacitors, and distribution line limits are the constraints of optimization problem.

In addition, loads and DGs are modeled as constant current. Therefore, load flow is implemented by the direct solution presented in [15] by building the bus-injection to branch-current (BIBC) and branch-current to bus-voltage (BCBV) matrices. The harmonic modeling of the network performed based on [16]. In addition, the relationship between the (harmonic) pseudo measurement error and the Standard Deviation (SD) is [17]:

$$\sigma_i = \frac{\mu_i \times error_i}{3 \times 100} \tag{4}$$

where

σ_i : the SD of *ith* pseudo measurement;

μ_i : the mean of *ith* pseudo measurement;

$error_i$: the maximum error (%) of *ith* pseudo measurement.

The number of measurements (PMUs) in distribution systems was selected so that full observability of the network is provided. Note that a PMU, which is available at any bus, can measure the phasor voltage of that bus and all phasor currents of the branches emanating from that bus [18]. In addition, these assumptions should be made:

- The status of the distribution lines and the switches is known.
- The number of the nonlinear loads is limited as well as the corresponding bus number, average, and SD is known.
- If the loads and the outputs of the DGs are fixed, the corresponding values and power factors are available.
- If the loads and the outputs of the DGs are variable, the average and the SD of corresponding outputs as well as the power factors are available.
- The set points of the VRs and the local capacitors are known.

IV. Application of Proposed MPSO to DHSE

In order to apply the MPSO to solve DHSE problem, the following steps should be done:

Step 1: Define the input data from PMUs and the network line parameters, topology, the pseudo measurements and the errors.
Step 2: Transfer the constraint HSE to the unconstraint HSE
Step 3: Generate the initial population
Step 4: Find *Pbest* and *Gbest* in the primary PSO using the constriction factor.
Step 5: If objective function value at *Gbest* < predefined error, run the ***secondary PSO*** and go to **Step 9**, otherwise continue.
Step 6: Update the position and the velocity of the particles using constriction factor in the primary PSO loop.
Step 7: Apply the ***mutation function***.
Step 8: If the termination criteria satisfy, continue, otherwise, go to **Step 4**.
Step 9: End

The termination criterion is the estimation error that can be set from 1e-3 to 1e-6. The overall flowchart of DSE based on proposed MPSO is shown in Fig. 2.

V. Uncertainty Analysis

To assess the uncertainty effects on the performance of the proposed DHSE algorithm based on MPSO, Monte Carlo simulation was performed. The uncertainties include the variations of harmonic pseudo measurement, the accuracy of the 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). In addition, all uncertainties are considered to have a Gaussian distribution. In order to consider such uncertainties, two steps were performed as follows:

1) First, 50 reference condition by randomly generating the variable loads and the outputs of the generators were created. Then the values of the PMUs were assigned from the load flow calculation for each reference individually.

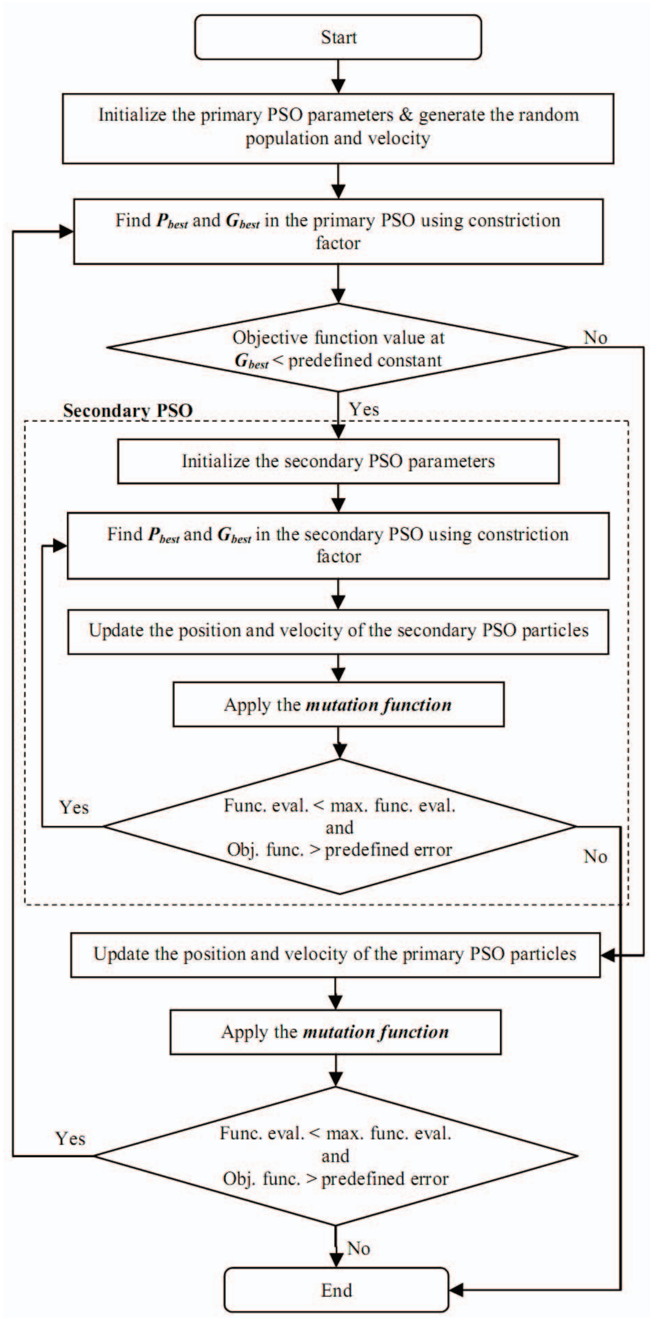

Fig. 2. DSE based on the proposed MPSO

2) Second, the error of measurements (PMUs) and the network parameters uncertainty were applied to each reference condition by using the Monte Carlo simulation. In this step, the values of the measurement error and the line impedance deviation were generated randomly over the predefined range. Then DHSE performed to estimate the injection harmonics. The number of Monte Carlo iterations for each reference condition was equal to 100. The tolerance of line parameters and the measurements' accuracy are considered 5% and 1%, respectively.
3) Third, the results of Monte Carlo simulation were compared with the bounds defined by the $\pm 3\sigma$ interval of the actual data of the injection harmonic.

VI. Simulation Results

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

Case 1: 34-bus IEEE 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:
- The specification of the injected harmonics of the loads and the WTs
- The tolerance of the line parameters
- The accuracy of the measurements.
- Values of PMUs
- Set points of the VRs and the local capacitors

In following, the results of two cases are presented.

A. Case 1: 34-bus IEEE radial test feeder

Figure 3 shows the 34-bus IEEE radial distribution test feeders whose associated specifications are presented in [19].

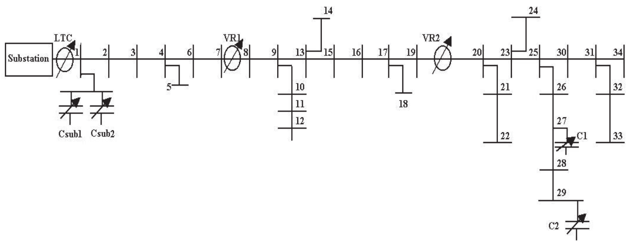

Fig.3. Single line diagram of IEEE 34-bus test system

In this case, there are three WTs connected at the buses 6, 17 and 29, whose specifications are presented in Table I. There are also 4 variable loads whose specifications are provided in Table II. In addition, there are three PMUs installed on the buses 1, 13, and 25.

The loads at the buses 22 and 30 and the WTs are nonlinear and inject some harmonics to the network. The harmonic specifications of them are presented in Table III.

Table I
Characteristic of Wind Generators

	WT1	WT2	WT3
Average of active power output (kW)	60	80	90
SD (%)	25	20	20
Power factor	0.8	0.8	0.8

Table II
Characteristic of Variable Loads

Bus no.	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)	SD (%)
2	0	0	32	16.5	26	14	50
22	27	22	27	22	27	22	50
27	134	107	134	107	134	107	20
30	20	16	20	16	62	38	50

Table III
Harmonic Characteristics of the Nonlinear Loads and the WTs (%)

Bus no. / WTs	5th 250 Hz	7th 350 Hz	11th 550 Hz	13th 650 Hz	SD
22	28	16	10	5	20
30	10	6	0	0	20
WTs	2.5	2.0	0.5	1.0	20

Tables IV and V show the estimated amplitudes and the phases of the harmonics for the load at the bus 22 by proposed MPSO, HBMO, WLS, GA, and original PSO for a predefined number of function evaluations. In addition, the average of relative errors in percent (*ARE %*) is reported.

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

Harmonic order	Amplitude (p.u.)	Mean of estimated amplitude (p.u.)				
		MPSO	HBMO	WLS	GA	orig. PSO
Fund. (50 Hz)	1.00	0.998	0.965	1.010	0.984	1.028
5^{th} (250 Hz)	0.28	0.279	0.253	0.238	0.301	0.263
7^{th} (350 Hz)	0.16	0.162	0.182	0.196	0.173	0.137
11^{th} (550 Hz)	0.10	0.103	0.083	0.131	0.077	0.115
13^{th} (650 Hz)	0.05	0.046	0.038	0.067	0.036	0.041
ARE %	-------	**1.916**	6.810	10.676	7.584	5.658

TABLE V
COMPARISON OF THE ESTIMATED PHASES OF HARMONICS FOR THE LOAD AT BUS 22 BY PROPOSED MPSO, HBMO, WLS, GA, AND ORIGINAL PSO

Harmonic order	Phase (degree)	Mean of estimated phase (degree)				
		MPSO	HBMO	WLS	GA	orig. PSO
Fund. (50 Hz)	-25	-24.9	-22.8	-28.4	-24.1	-25.5
5^{th} (250 Hz)	75	75.6	82.2	62.1	86.3	67.4
7^{th} (350 Hz)	-165	-162.7	-151.1	-192.8	-140.2	-183.5
11^{th} (550 Hz)	-65	-68.2	-50.7	-43.7	-76.4	-75.9
13^{th} (650 Hz)	-105	-95.4	-128.6	-70.3	-135.8	-122.8
ARE %	------	**2.103**	7.014	10.827	8.084	5.660

As shown, the *ARE%* of the amplitudes as well as the phases estimated based on the MPSO is lower than the *ARE%* computed based on other algorithms. In addition, the *ARE%* of the amplitudes is less than the *ARE%* of the phases estimated based all algorithms. Table VI shows the simulation results for the Maximum Individual Relative Error (*MIRE %*) as:

$$MIRE(\%) = \max(|X_{est}(i) - X_{true}(i)| / |X_{true}(i)|) \times 100 \quad (5)$$

TABLE VI
COMPARISON OF MIRE FOR ESTIMATED VALUES

		MPSO	HBMO	WLS	GA	orig. PSO
MIRE %	Amplitude	9	24	34	28	18
	Phase	9	22	33	29	17

In addition, Table VII presents the number of function evaluations to solve the DHSE for a predefined estimation error based on all algorithms, individually.

TABLE VII
COMPARISON OF NUMBER OF FUNCTION EVALUATIONS

Method	MPSO	HBMO	WLS	GA	orig. PSO
Number of function evaluations	455	560	790	950	650

For uncertainty analysis of the MPSO-based DHSE, the Monte Carlo simulations as described in Section V were performed. This simulation showed that the mean of the estimated amplitudes as well as the mean of the phases are within the bounds obtained from the actual values±3σ interval when the proposed MPSO algorithm was applied to DHSE. The values of σ were calculated from the corresponding SD of variables gained from the Monte Carlo simulation. The actual and estimated values of 5^{th} harmonic amplitudes of the nonlinear loads and the WTs as well as corresponding the actual values±3σ interval for one reference are shown in Fig. 4. For a better overall view, all values in Fig. 4 are divided by their actual values. The same results were obtained for other harmonic order and for other reference conditions, which were mentioned in Section V.

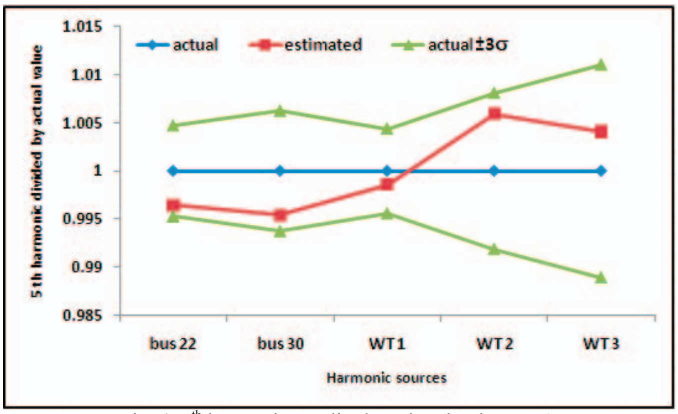

Fig. 4. 5^{th} harmonic amplitude estimation in case 1.

B. Case 2: A realistic 70-bus test network

Figure 5 shows the 70-bus test feeders whose associated specifications are presented in [20]. In this case, six WTs whose parameters are presented in Table VIII are connected to the network. There are 8 variable loads in the network whose specifications are demonstrated in Table IX. In addition, there are six PMUs installed on the buses 1, 7, 17, 40, 52, and 70.

The loads at the buses 4, 14 and 42 and the WTs are nonlinear and inject harmonics to the network. The injection harmonic specifications are presented in Table X.

In order to perform a better comparison between case studies, the results of DSE is presented for the load at the bus 4 that harmonic specifications are similar to the load at the bus 22 in the previous case study. Table XI and XII show the estimated amplitudes and phases of the injection harmonics of the load at the bus 4 by proposed MPSO, HBMO, WLS, GA, and original PSO for a predefined number of function evaluations. Moreover, the average of relative errors in percent (*ARE %*) is reported.

The results showed that the *ARE%* of the amplitudes as well as the phases estimated based on proposed MPSO is lower than the *ARE%* computed based on the other mentioned algorithms. In addition, the *ARE%* of the amplitudes is less than the *ARE%* of the phases estimated based all algorithms. Tables XIII shows the simulation results for the *MIRE %*. In addition, Tables XIV presents the number of function evaluations to solve the DHSE for a predefined estimation error based on MPSO and other algorithms.

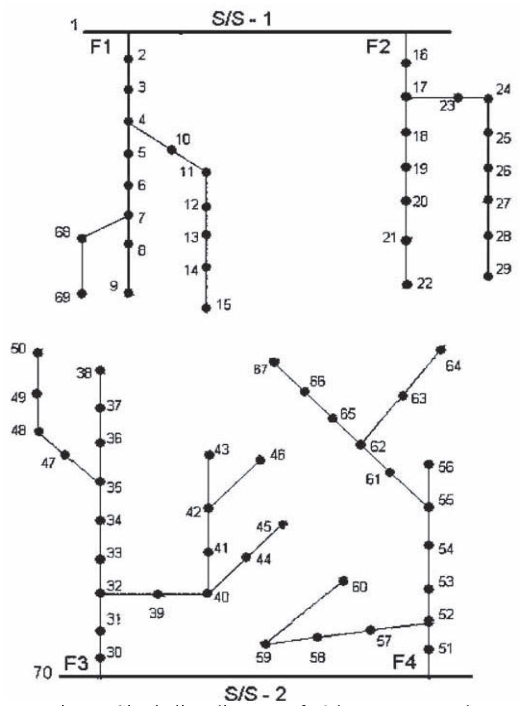

Fig. 5. Single line diagram of 70 bus test network

TABLE VIII
CHARACTERISTIC OF WIND GENERATORS

No.	Average of active power output (kW)	SD (%)	Bus no.	Power factor
WT1	300	10	8	0.9
WT2	350	15	29	0.9
WT3	650	15	35	0.9
WT4	500	10	41	0.9
WT5	200	15	62	0.9
WT6	300	20	58	0.9

TABLE IX
CHARACTERISTIC OF VARIABLE LOADS

Bus no.	Active power (kW)	Reactive power (kVar)	SD (%)
4	100	30	50
14	320	230	30
26	210	134	30
21	150	86	20
34	260	134	50
42	170	93	20
53	230	134	30
64	400	183	50

TABLE X
HARMONIC CHARACTERISTICS OF NONLINEAR LOADS AND WTS (%)

Bus no. / WTs	5th 250 Hz	7th 350 Hz	11th 550 Hz	13th 650 Hz	SD
4	28	16	10	5	20
14	10	6	0	0	20
42	15	10	5	0	20
WTs	2.5	2.0	0.5	1.0	20

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

Harmonic order	Amplitude (p.u.)	Mean of estimated amplitude (p.u.)				
		MPSO	HBMO	WLS	GA	orig. PSO
Fund. (50 Hz)	1.00	0.998	0.965	1.011	0.984	1.028
5th (250 Hz)	0.28	0.279	0.251	0.234	0.306	0.261
7th (350 Hz)	0.16	0.162	0.185	0.199	0.177	0.135
11th (550 Hz)	0.10	0.103	0.081	0.138	0.072	0.116
13th (650 Hz)	0.05	0.045	0.036	0.072	0.034	0.040
ARE %	-------	**2.105**	7.768	13.031	8.966	6.177

TABLE XII
COMPARISON OF THE ESTIMATED PHASES OF HARMONICS FOR THE LOAD AT BUS 4 BY PROPOSED MPSO, HBMO, WLS, GA, AND ORIGINAL PSO

Harmonic order	Phase (degree)	Mean of estimated phase (degree)				
		MPSO	HBMO	WLS	GA	orig. PSO
Fund. (50 Hz)	-25	-24.9	-22.8	-28.5	-24.0	-25.7
5th (250 Hz)	75	75.6	82.2	60.1	87.2	65.3
7th (350 Hz)	-165	-162.7	-150.0	-198.7	-140.2	-186.5
11th (550 Hz)	-65	-68.3	-48.5	-39.6	-78.4	-78.6
13th (650 Hz)	-105	-94.8	-131.7	-61.4	-139.9	-131.2
ARE %	------	**2.217**	7.857	13.052	9.025	7.497

TABLE XIII
COMPARISON OF MIRE FOR ESTIMATED VALUES

		MPSO	HBMO	WLS	GA	orig. PSO
MIRE (%)	Amplitude	10	28	44	32	20
	Phase	10	25	42	33	25

TABLE XIV
COMPARISON OF NUMBER OF FUNCTION EVALUATIONS

Method	MPSO	HBMO	WLS	GA	orig. PSO
Number of function evaluations	570	770	1150	1350	870

Figure 5 shows the actual and estimated values of 5th harmonic amplitudes as well as corresponding ±3σ in respect to the actual values for one reference condition in Case 2.

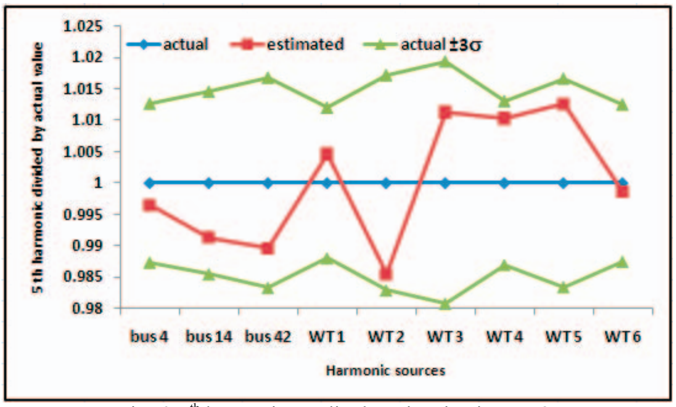

Fig. 6. 5th harmonic amplitude estimation in case 2.

As shown in Fig. 6, same as the previous case study, the mean of the estimated amplitudes as well as the mean of the phases are within the bounds obtained from the ±3σ interval of the actual values when the proposed MPSO algorithm was applied to DHSE. In addition, for a better overall view, all values in Fig. 4 are divided by their actual values. The same results were obtained for other harmonic order and for other reference conditions mentioned in Section V.

VII. CONCLUSION

A new algorithm based on a Modified Particle Swarm Optimization (MPSO) to Distribution Harmonic State Estimation (DHSE) was presented. The proposed MPSO for the estimation of both amplitude and phase of injection harmonic currents includes a primary PSO loop, a secondary PSO loop, and the mutation function. Two radial case studies (34-bus IEEE and 70-bus realistic) comprising the nonlinear loads and wind turbines was performed by using the Phasor Measurement Units (PMUs) data. The simulations showed that the speed and the accuracy of the proposed MPSO-based DHSE are excellent in comparison with the Weight Least Square (WLS), Genetic Algorithm (GA), original PSO, and Honey Bees Mating Optimization (HBMO) algorithms.

In addition, the uncertainty analysis was performed by Monte Carlo simulation. The uncertainties to be involved are the variations of harmonic pseudo measurement, the accuracy of the measurement, and the tolerance in the line impedances as well as the uncertainties of the wind turbines. This analysis showed that the mean of the estimated amplitudes as well as the mean of the phases are within the bounds obtained from the $\pm 3\sigma$ interval of the actual values when the proposed MPSO algorithm was applied to DHSE for all harmonic levels.

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IX. Biographies

Ali Arefi received his B.Sc. and M.Sc. in electrical engineering from Sharif University of Technology, Tehran, Iran, in 1999 and 2001, respectively. At present, He is a PhD student at Tarbiat Modares University, Tehran, Iran. His main fields of interest are state estimation, energy efficiency, and power quality.

Mahmood Reza Haghifam (M'98–SM'06) received his B.Sc. degree from Tabriz University, Tabriz, Iran, in 1988, M.Sc. degree from Tehran University, Tehran, Iran, in 1990 and PhD degree from Tarbiat Modares University, Tehran, Iran in 1995. In 1995, he joined the Tarbiat Modares University, where he is currently a Professor of Electric Power Systems. His current research interests include power system reliability, electric distribution systems, and soft computing application in power systems. Prof. Haghifam is a Research Fellow of the Alexander Von Humboldt Foundation, Germany.

Seyed Hamid Fathi received his B.Sc. degree in Electrical Engineering from Amirkabir University of Technology, Tehran, Iran, in 1984, M.Sc. in Electrical Engineering (Power) from Iran University of Science & Technology, Tehran, Iran, 1987 and PhD in Electrical Engineering (Power Electronics) from the University of Newcastle upon Tyne, UK, in 1991. In 1991, he joined Amirkabir University of Technology, where he is currently the Associate Professor of Electric Power Systems. His current research interests include power quality and reactive power control in electric systems, power electronics, and drives.