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A Novel Algorithm Based on Honey Bee Mating Optimization for Distribution Harmonic State Estimation Including Distributed Generators

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Abstract: **This paper presents a new algorithm based on Honey-Bee Mating Optimization (HBMO) to estimate harmonic state variables in distribution networks including Distributed Generators (DGs). The proposed algorithm performs estimation for both amplitude and phase of each harmonics 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. Simulation results on two distribution test system are presented to demonstrate that 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) and Tabu Search (TS).**

***Index Terms*--** **Distributed Generators, Harmonic State Estimation, Honey-Bee Mating Optimization, Distribution System.**

I. NOMENCLATURE

N_c	number of capacitors
N_g	number of DGs
N_s	number of harmonic amplitude or phase state variables
N_t	number of transformers and VRs
N_b	number of buses
N_L	number of loads
$\overline{X}$	state variables vector
z_i	measured values
ω_i	weighting factor of the i^{th} measured variable
h_i	state equation of the i^{th} measured variable
m	number of measurements
AH^i	amplitude of injected harmonics corresponding to i^{th} nonlinear load
PH^i	phase of injected harmonics corresponding to i^{th} nonlinear load
$P^i_{G,min}$	minimum power of the i^{th} DGs
$P^i_{G,max}$	maximum power of the i^{th} DGs
$\left\lvert P_{ij}^{Line} \right\rvert$	absolute power flowing between the nodes i and j
$P_{ij,\max}^{Line}$	maximum transmission power between the nodes i and j
$Tap_i^{\min}$	minimum tap positions of the i^{th} transformer
$Tap_i^{\max}$	maximum tap positions of the i^{th} transformer
Tap_i	current tap positions of the i^{th} transformer
$AH_i^{\min}$	minimum amplitude of injected harmonics corresponding to i^{th} nonlinear load
$AH_i^{\max}$	maximum amplitude of injected harmonics corresponding to i^{th} nonlinear load
$PH_i^{\min}$	minimum phase of injected harmonics corresponding to i^{th} nonlinear load
$PH_i^{\max}$	maximum and current phase of injected harmonics corresponding to i^{th} nonlinear load
V_{max}	maximum value of voltage magnitude
V_{min}	minimum value of voltage magnitude
$P^i_{Load,max}$	maximum active power of the i^{th} load
$P^i_{Load,min}$	minimum active power of the i^{th} load
Q_c^i	reactive power of the i^{th} capacitor
$Q^i_{c,max}$	maximum reactive power of the i^{th} capacitor
$Prob(D)$	probability of adding the sperm of drone D to the spermatheca of the queen
$\Delta(f)$	absolute difference between the fitness of D and the fitness of the queen
$S(t)$	speed of the queen at time t
α	speed reduction schema, a factor $\in (0,1)$
S_{max}	speed of queen at the start of a mating flight
S_{min}	speed of queen at the end of a mating flight
N_{Worker}	number of workers
N_{Dreone}	number of drones
N_{Sperm}	size of the queen's spermatheca
N_{Brood}	number of broods
$rand(.)$	a random function generator
D_i	i^{th} drone
Sp_i	i^{th} individual in the queen's spermatheca
β	a random number between 0 and 1
$Brood_j$	j^{th} brood
x_j	j^{th} control variable
N	number of control variables
$x^j_{\max}$	maximum values of the j^{th} state variables
$x^j_{\min}$	minimum values of the j^{th} state variables
X_{est}	estimated harmonic values
X_{true}	actual harmonic values

II. INTRODUCTION

A direct result of energy needs meeting environmental and social concerns is the growing interest in reliable and renewable energy sources. We believe the future will bring us more and more small distributed power generation units connected to the grid. Study and investigating of the grid integration of DGs lead researches in focusing on the rise of DGs' harmonic injection and the voltage quality of such

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distributions grids. In a deregulated electricity industry, new concerns have emerged regarding the quality of power supply as each company involved will focus on its own objectives and interest. One of the main concerns regarding the quality of power supply is the harmonic pollution. In a deregulated environment, obtaining sufficient harmonic measurements throughout the network becomes an issue because the cost of taking measurement and the different ownership of different parts of the system. Since measurement of all loads and DG outputs in distribution network of a company is not feasible and economical, Several HSE techniques have been developed for harmonic source identification in recent years. In addition, HSE is a platform of power quality judgment and penalty in restructuring environment.

In the late l980's, Heydt put forward the problem of harmonic state estimation [1] and applied the method used in power system state estimation to the harmonic state estimation. Meliopoulos [2] utilized WLS approach to estimate harmonics amplitude in electrical network with synchronized measurement. The Kalman filtering approach has also been frequently employed to estimate different states and parameters of integral harmonics in an electrical signal [3]. Reference [4] examines singular value decomposition (SVD) for the estimation of harmonics in electric network in the presence of high noise. 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 power-quality (PQ) indices estimation according to the power components and PQ indices definitions given in the IEEE Standard 1459–2000 is introduced in [6]. A new algorithm is presented in [7] based on the particle swarm optimizer with passive congregation (PSOPC) to estimate the phases of the harmonics, alongside a least-square (LS) method that is used to estimate the amplitudes.

In the conventional methods, it is assumed that the objective functions and constraints should be continuous and differentiable. However, due to the existence of distributed generation and nonlinear modeling of some distribution network elements, these methods could not be easily used. To solve such problem, evolutionary methods and expert systems such as neural networks, genetic algorithms, can be utilized. But some evolutionary methods neither reach global minima nor have short convergence time.

Recently, a new optimization algorithm based on honey bee mating has been used to solve difficult optimization problems such as optimal reservoir operation and clustering. The Honey Bee Mating Optimization algorithm was first presented in [8] and [9], and since then it was used on a number of different applications ([8-10]). The Honey Bees Mating Optimization (HBMO) algorithm simulates the mating process of the queen of the hive.

In this paper, a new algorithm based on HBMO for a practical distribution HSE including DGs is presented. In this method, DGs and loads that do not have constant output are considered as the state variables in which the differences between measured and calculated values are assumed as the objective function.

Since, in many cases, estimation of all harmonic states is not necessary, that is, only the suspicious load’s harmonics are estimated, in this paper, estimation of some load’s harmonics have been done. However, the proposed algorithm is applicable for harmonic estimation of all states.

In the following section, the distribution HSE problem is formulated. In section IV, a distributed generator modeling is presented. The HBMO is introduced in section V. Application of the proposed algorithm to distribution state estimation is shown in section VI. Finally, in section VII, the feasibility of the proposed approach is demonstrated and compared with estimators which are based on WLS, GA and TS for two test systems.

III. DISTRIBUTION STATE ESTIMATION INCLUDING DISTRIBUTED GENERATORS

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

A) Objective function:

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

where: $\overline{X}$ is the state variables vector including the some states’ harmonics (amplitude and phase) injections.

B) Constraints

Constraints are defined as follows:

- Active power constraints of DGs:

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

- Distribution line limits:

$$\left| P^{Line}_{ij} \right| < P^{Line}_{ij,\max} \tag{3}$$

- Harmonics:

$$AH_i^{\min} < AH_i < AH_i^{\max} \qquad i = 1, 2, ..., N \tag{4}$$

$$PH_i^{\min} < PH_i < PH_i^{\max} \qquad i = 1, 2, ..., N \tag{5}$$

- Tap of transformers:

$$Tap_i^{\min} < Tap_i < Tap_i^{\max} \qquad i = 1, 2, ..., N_t \tag{6}$$

- Bus voltage magnitude

$$V_{\min} \le V_i \le V_{\max} \qquad i = 1,2,3, \ \dots, N_b \tag{7}$$

- Active power constraints of loads:

$$P^i_{Load,min} \le P^i_{Load} \le P^i_{Load,max} \qquad i = 1,2,3,...N_L \tag{8}$$

- Reactive power constraint of capacitors

$$0 \le Q_c{}^i \le Q^i_{c,\,max} \qquad i = 1,2,3,..., \ N_c \tag{9}$$

- Unbalanced three-phase power flow equations.

It is assumed, in this paper, that capacitors and VRs, which change stepwise and are installed along feeders, are locally controlled. During the search procedure, change of state variables (some states' harmonics injections) may cause change of tap positions and capacitor banks, which consequently make the objective function change non-continuously.

The number of measurements in distribution systems is usually less than that of the state variables. In order to have a unique solution, these assumptions should be made:

- Status of distribution lines and switches is known.
- Harmonic injection by DGs is zero.
- The number of nonlinear loads is limited and corresponding bus number, average and standard deviation is known.
- A contracted load and distributed generation values are known at each node.
- Voltage, current and harmonics at the substation bus (main bus) are known.
- If outputs of DGs and loads are fixed, the outputs and power factors will be available.
- If outputs of DGs and loads are variable, the average outputs, the standard deviations and the power factors can be obtained.
- Set points of VRs and local capacitors are known.

In this paper, average outputs and standard deviations of DGs and loads, which are variable, are considered as pseudo instrument devices. The value of ω_i for real instrument devices should be considered high and for pseudo instrument devices should be considered low. In this paper these values are 100 and 0.1, respectively. Moreover, all of electrical parameters are calculated true RMS based on references [16].

IV. DISTRIBUTED GENERATOR MODELING

DGs, modeled as PV or PQ, can be controlled and operated in unbalanced distribution systems in two forms [11, 12]:

- Simultaneous three-phase control
- Independent three-phase or single phase control

In regards to these control methods and DGs models, four simulation models have been presented for DGs described in Fig. 1 [11, 12]:

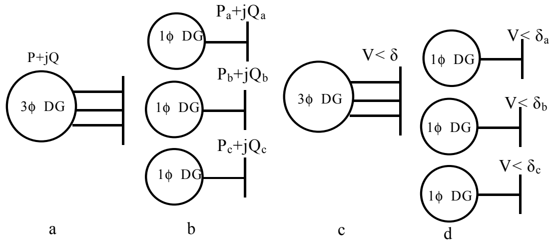

Fig. 1. Models of DGs
(a). PQ Model with simultaneous three-phase control
(b). PQ Model with independent three- phase control
(c). PV Model with simultaneous three- phase control
(d). PV Model with independent three- phase control

DGs modeled as PV have to be able to generate reactive power to maintain their voltage magnitudes. In this paper, DGs are modeled as the PQ buses with simultaneous three-phase control.

V. HONEY-BEE MODELING

A colony of honey bees is consist of a queen, several hundred drones, 30,000 to 80,000 workers and broods during the active season. The queen, only, has capable of laying eggs up to 1,500 during a 24-hour period. Drones' role is to mate with the queen. Tasks of worker bees are several such as: rearing brood, tending the queen and drones, cleaning, regulating temperature, gather nectar, pollen, water, etc.

The HBMO Algorithm is the combination of several different methods corresponded to a different phase of the mating process of the queen that is presented in Fig. 2. [8]

The main stages of HBMO algorithm Based on mating are given below:

- Starting the mating flight, where a queen (best solution) selects drones to form the spermatheca (list of drones) probabilistically. Next, a drone is selected from the mentioned list randomly for the generation of broods.
- Generation of new broods (solutions) with crossover genotypes of the drone's and the queen's.
- Local searching on broods (trial solutions) by the workers.
- Adaptation of worker's fitness, based on the amount of improvement achieved on broods.
- Replacing the weaker queens by better broods.

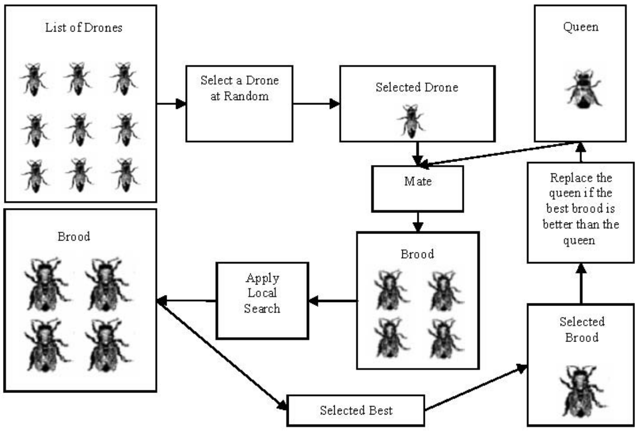

Fig. 2. The HBMO algorithm

Before the beginning of mating process, the queen's size of spermatheca number equals to the maximum number of mating of the queen in a single mating flight is determined. When the queen mates successfully, the genotype of the drone is stored. Two other parameters have to be defined, the number of queens and the number of broods that will be born by all queens.

In this implementation of HBMO algorithm, the number of queens is set equal to be one, and the number of broods is set equal to the number of the queen's spermatheca size. also, the queen is initialized with some energy content and returns to hive either the energy is to decrease to minimum threshold level or its spermatica is full [10].

A drone mates with a queen probabilistically using an annealing function as follows [13]:

$$\Pr ob(D) = \exp(-\Delta(f)/S(t)) \qquad (10)$$

When the queen is with the high speed level or the fitness of the drone is as good as the queen's, the probability of mating is high. After each flying, the queen's speed and energy decrease according to the following equations:

$$S(t+1)=\alpha\times S(t) \tag{11}$$

$$Energy(t+1)=\alpha\times Energy(t) \tag{12}$$

where α is the speed and energy reduction factor after each step. Initially, the speed and the energy of the queen are generated at random. Since the speed and energy have the same effect on mating process, in this paper, speed of queen has been used. If the mating is successful (i.e., the drone passes the probabilistic decision rule), the drone's sperm is stored in the queen's spermatheca. A new brood is generated by the drone's and the queen's genotypes crossover. This brood can be improved, in the next stage, by employing workers to apply local search.

In HBMO algorithm, the queen stores a several number of drone's sperm in spermatheca to create a new solution to have possibility of fittest broods more. This is the excellence of the HBMO on the classic evolutionary algorithms.

The workers implement the local search procedures to improve the broods produced by the mating process. Since the workers have different capabilities and the choice of two different workers may apply different solutions. This is implemented by using a number of local search heuristics ($N_{Worker1}$) and combinations of them ($N_{worker2}$). Therfore, the number of workers is calculated by the sum of these two numbers ($N_{Worker} = N_{Worker1} + N_{worker2}$).

VI. PROPOSED ALGORITHM BASED ON HBMO TO HSE

The application of the proposed algorithm to solve distribution harmonic estimation presents in this section. It should be noted that the state variables are nonlinear loads' harmonics. In order to apply the HBMO to solving DHSE, the following steps should to be done:

Step 1: Gather the input data.

the input data are defined such as: the real and pseudo measured values, the average and standard deviation of loads and DGs, the starting (S_{max}) and ending (S_{min}) speed of queen at mating flight, the speed reduction factor (α), the number of iteration, the number of workers (N_{Worker}), the number of drones (N_{Dreone}), the size of the queen's spermatheca (N_{Sperm}) and the number of broods ($\mathrm{N_{Brood}}$).

Step 2: Transfer the constraint HSE to the unconstraint HSE.

The proposed DHSE problem needs to be transformed into an unconstrained one.

Step 3: Generate the initial population.

An initial population based on state variable is generated, randomly and formulated as:

$$\begin{aligned}
&Population=\left[\overline{X_1}\quad \overline{X_2}\quad \ldots\quad \overline{X_N}\right]^T\\
&\overline{X_i}=[x_j]_{1\times n}=[\overline{AH_i},\overline{PH_i}]\\
&\overline{AH_i}=[AH_i^1,AH_i^2,\ldots,AH_i^{Ns}]\\
&\overline{PH_i}=[PH_i^1,PH_i^2,\ldots,PH_i^{Ns}]\\
&i=1,2,3,\ldots\ldots N
\end{aligned} \tag{13}$$

where n is the number of state variables. N is the number of members in initial population.

Step 4: Calculate the value of objective function.

In this step, the objective function is evaluated for each individual by utilizing the result of distribution harmonic load flow.

Step 5: Sort the initial population based on the objective function values.

The initial population is ascending based on the value of the objective function.

Step 6: Select the queen.

The individual that has the minimum objective function should be selected as the queen $(\overline{X}_{best})$.

Step 7: Generate the speed of the queen.

The queen speed is randomly generated as:

$$S_{queen}=rand(.)\times(S_{\max}-S_{\min})+S_{\min} \tag{14}$$

Step 8: Select the population of drones.

The population of drones is selected from the sorted initial population as following:

$$\begin{aligned}
&Drone\_Population=\left[D_1\quad D_2\quad \ldots\quad D_{N_{Drone}}\right]^T\\
&D_i=[\overline{AH_i},\overline{PH_i}]\\
&i=1,2,3,\ldots.,N_{Drone}
\end{aligned} \tag{15}$$

Step 9: Generate the queen's spermatheca matrix.

At the start of the mating flight, a drone is selected randomly. A number between 0 and 1 generated randomly is compared with the mating probability. If the number is less than the mating probability, the drone's sperm is sorted and the queen speed is decreased. Otherwise, the queen speed is decreased and another drone from the population of drones is selected until the speed of the queen reaches to minimum level or the queen's spermatheca is full.

$$\begin{aligned}
&Spermacthcca\_matrix=\left[Sp_1\quad Sp_2\quad \ldots\quad Sp_{N_{Sperm}}\right]^T\\
&Sp_i=[s_j]_{1\times n}=[\overline{AH_i},\overline{PH_i}]\\
&i=1,2,3,\ldots,N_{Sperm}
\end{aligned} \tag{16}$$

Step 10: Breeding process.

In this step, a population of broods is generated based on mating between the queen and the drones stored in the queen's spermatheca as described follow for the j^{th} brood:

$$\begin{aligned}
&\overline{X}_{best}=\left[x_{best}^1\quad x_{best}^2\quad \ldots\quad x_{best}^n\right]\\
&Sp_i=\left[s_i^1\quad s_i^2\quad \ldots\quad s_i^n\right]\\
&Brood_j=\overline{X}_{best}+\beta\times(\overline{X}_{best}-Sp_i)\\
&j=1,2,3,..N_{Brood}
\end{aligned} \tag{17}$$

Step 11: Improve the selected broods by workers.

The population of broods is improved by applying some heuristic mutation functions as: At first the i^{th} brood is randomly selected. Two integer numbers ($B1$ and $B2$) between 1 and n are randomly generated. It is assumed $B1 < B2$. The brood is changed and improved as below:

$$\begin{aligned}
&Brood_i(j)=Brood_i(j) \qquad if \quad j<B1\\
&Brood_i(j)=rand(.)\times(x_{\max}^j-x_{\min}^j)+x_{\min}^j, if \quad B1\le j\le B2\\
&Brood_i(j)=Brood_i(j) \qquad if \quad j>B2\\
&i=1,2,3,\ldots,N_{Worker}
\end{aligned} \tag{18}$$

Step 12: Calculate the objective function value for the new generated population.

The objective function is to be calculated for each individual of the new generated population by using the result of distribution harmonic load flow. If the new best solution is better than the queen, replace it with queen.

Step 13: Check the error to terminate.

If the error criteria satisfied finish the algorithm, else discard all previous trial solutions and go to step 3 until convergence criteria met.

VII. SIMULATION RESULTS

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

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

Case 2: A realistic 70-bus test network: including 6 DGs.

It is assumed that the following information is available.

- Values of deviations of injected harmonics for loads.
- Values of PMUs
- Set points of VRs and local capacitors

In following, results for two cases are presented.

Case 1: IEEE 34 bus radial test feeder

Fig. 3. shows the IEEE 34 bus radial distribution test feeders whose associated specifications are presented in [14].

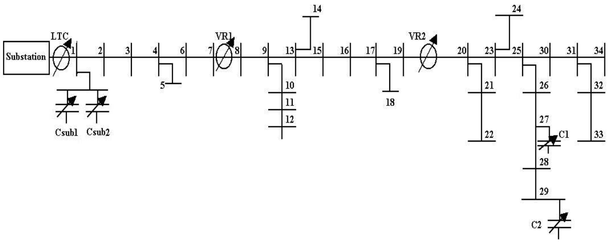

Fig.3. Single line diagram of IEEE 34-bus test system

For this system it is assumed that there are three DGs 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.

It is assumed that there are three PMUs installed on buses 1, 15 and 25.

TABLE I

CHARACTERISTIC OF GENERATORS

	G1	G2	G3
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 are nonlinear loads and inject harmonics to network. The harmonic specifications are presented in Table III. Also, it is assumed that the DG outputs are harmonic free.

TABLE III

HARMONIC CHARACTERISTICS OF NONLINEAR LOADS (%)

Load Bus No.	5th (250 Hz)	7th (350 Hz)	11th (550 Hz)	13th (650 Hz)	Standard Deviation (%)
22	15.5	10.3	3.4	3.1	20
30	10	6	0	0	20

In order to find the best value of the HBMO Algorithm parameters such as the speed of queen at the start of a mating flight (S_{max}), the speed of queen at the end of a mating flight (S_{min}), the speed reduction schema (α), etc., a simulation has done to determine each parameter.

The best values for mentioned parameters are selected by several trials as follows: S_{max} =1, S_{min} =0.1, α=0.95, N_{Worker} =20, N_{Dreone}=30, N_{Sperm} =20, N_{Brood} =20.

Tables IV and V show the estimated harmonics amplitudes and phase of for the load at bus 22 by HBMO, WLS, GA, and TS. The l^2-norm criterion has applied for error.

TABLE IV

COMPARISON OF THE ESTIMATED AMPLITUDES OF HARMINICS FOR THE LOAD AT BUS 22 BY HBMO, WLS, GA, AND TS

Harmonic Order	Amplitude (P.U.)	Estimated Amplitude (P.U.)			
		HBMO	WLS	GA	TS
Fund. (50 Hz)	0.97	0.967	1.000	0.980	0.990
5th (250 Hz)	0.15	0.147	0.200	0.120	0.110
7th (350 Hz)	0.1	0.099	0.080	0.085	0.110
11th (550 Hz)	0.033	0.032	0.010	0.025	0.040
13th (650 Hz)	0.03	0.031	0.045	0.019	0.050
error (%)		0.4640	6.8329	3.8021	5.1121

TABLE V

COMPARISON OF THE ESTIMATED PHASES OF HARMINICS FOR THE LOAD AT BUS 22 BY HBMO, WLS, GA, AND TS

Harmonic Order	Phase (degree)	Estimated Phase (Degree)			
		HBMO	WLS	GA	TS
Fund. (50 Hz)	-1.0	-0.99	-0.95	-0.97	-0.96
5th (250 Hz)	80.0	81	72	76	85
7th (350 Hz)	8.0	7.9	7.3	7.5	8.6
11th (550 Hz)	-155.0	-154	-149	-150	-161
13th (650 Hz)	170.0	171	178	163	177
error (%)		0.7119	5.2628	3.8982	4.3107

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

$$MIRE(\%) = \max(|X_{est}(i) - X_{true}(i)| / |X_{true}(i)|) \times 100 \qquad (19)$$

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

TABLE VI

COMPARISON OF MIRE FOR ESTIMATED VALUES

		HBMO	WLS	GA	TS
MIRE(%)	Amplitude	0.022	0.6500	0.2100	0.3300
	Phase	0.053	0.4500	0.2500	0.2800

TABLE VII

COMPARISON OF NUMBER OF FUNCTION EVALUATIONS

Method	HBMO	WLS	GA	TS
NUMBER OF FUNCTION EVALUATIONS	370	430	560	715

Case 2: A realistic 70-bus test network

Fig. 4. shows the 70-bus test feeders whose associated specifications are presented in [15]. For this system it is assumed that there are eight DGs whose parameters are presented in Table VIII. There are also 8 variable loads whose specifications are demonstrated in Table IX.

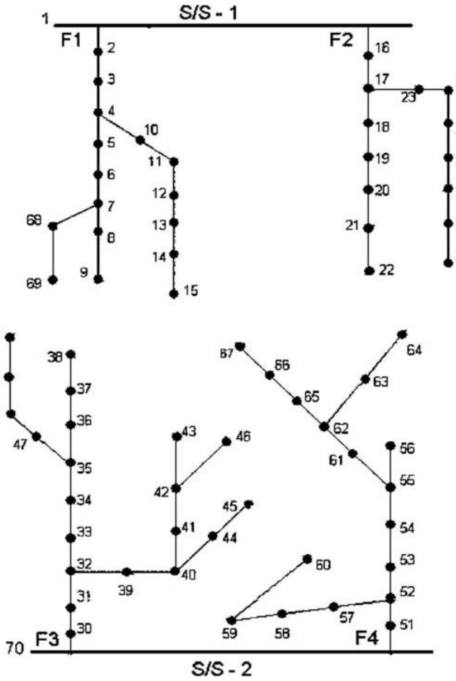

Fig. 4. Single Line Diagram of 70 bus test network

TABLE VIII
CHARACTERISTIC OF GENERATORS

	Average of active power output (kW)	Standard deviation (%)	location	Power factor
G1	300	10	8	1
G2	450	15	14	1
G3	500	10	21	1
G4	350	15	29	1
G5	650	15	35	1
G6	500	10	41	1
G7	200	15	62	1
G8	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

It is assumed that there are eight PMUs installed on buses 1, 70, 6, 10, 18, 25, 47 and 40.

The loads at buses 4, 14 and 42 are nonlinear loads and inject harmonics to network. The harmonic specifications are presented in Table X. Also, it is assumed that the DG outputs are harmonic free.

Tables XI and XII show the estimated amplitudes and phase of harmonics for the load at bus 22 by HBMO, WLS, GA, and TS. The l^2-norm criterion has applied for error.

TABLE X
HARMONIC CHARACTERISTICS OF NONLINEAR LOADS (%)

Load Bus No.	5th (250 Hz)	7th (350 Hz)	11th (550 Hz)	13th (650 Hz)	Standard Deviation (%)
4	15.5	10.3	3.4	3.1	20
14	10	6	0	0	15
42	15	10	5	0	10

TABLE XI
COMPARISON OF THE ESTIMATED AMPLITUDES OF HARMINICS FOR THE LOAD AT BUS 4 BY HBMO, WLS, GA, AND TS

Harmonic Order	Amplitude (P.U.)	Estimated Amplitude (P.U.)			
		HBMO	WLS	GA	TS
Fund. (50 Hz)	0.97	0.961	1.01	0.99	1.03
5th (250 Hz)	0.15	0.143	0.22	0.11	0.17
7th (350 Hz)	0.1	0.091	0.075	0.088	0.12
11th (550 Hz)	0.033	0.029	0.037	0.021	0.038
13th (650 Hz)	0.03	0.025	0.049	0.04	0.045
error (%)		1.6074	8.7700	4.9480	6.9046

TABLE XII
COMPARISON OF THE ESTIMATED PHASES OF HARMINICS FOR THE LOAD AT BUS 4 BY HBMO, WLS, GA, AND TS

Harmonic Order	Phase (degree)	Estimated Phase (Degree)			
		HBMO	WLS	GA	TS
Fund. (50 Hz)	-1.0	-0.96	-0.93	-0.94	-0.91
5th (250 Hz)	80.0	77	71	89	69
7th (350 Hz)	8.0	8.2	8.5	7.5	9.1
11th (550 Hz)	-155.0	-158	-145	-161	-141
13th (650 Hz)	170.0	173	180	157	179
error (%)		2.1338	6.8817	6.9425	8.1988

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

TABLE XIII
COMPARISON OF MIRE FOR ESTIMATED VALUES

		HBMO	WLS	GA	TS
MIRE(%)	Amplitude	0.0520	0.7500	0.6100	0.9300
	Phase	0.0900	0.8500	0.7500	0.6800

TABLE XIV
COMPARISON OF NUMBER OF FUNCTION EVALUATIONS

Method	HBMO	WLS	GA	TS
NUMBER Of Function EVALUATIONS	760	850	1230	1580

VIII. CONCLUSION

Since the number of nonlinear loads will be increasing, the study of impact of them on distribution systems it is a vital task. In this paper, a novel algorithm called HBMO to estimate amplitude and phase of some harmonic state variable in distribution network in the presence of DGs was discussed and investigated in detail. HBMO; the powerful optimization algorithm was examined on two test systems: IEEE 34 bus radial test feeder and a 70-bus radial distribution test feeders. The proposed algorithm is successful to find the global optimum. In regards to expense of computation, the number of function evaluations, and errors for estimated values, HBMO shows very excellent performance to WLS, GA and TS. These results lead us to conclude that the HBMO based algorithm is truly efficient, effective, and robust to reach optimum solutions for practical and complex DHSE problems. Also, it can handle and solve the nondifferential and noncontinuous objective function of DHSE caused by nonlinear characteristics of the nonlinear loads and equipments such as Var Compensators, VRs, and ULTC transformer model. Also, the proposed method could be applied to a wide variety of similar problems.

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