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Optimal Placement and Sizing of Inverter-Based Distributed Generation Units and Shunt Capacitors in Distorted Distribution Systems Using a Hybrid Phasor Particle Swarm Optimization and Gravitational Search Algorithm

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CONTENTS

Abstract—In this paper, a novel hybrid population-based meta-heuristic algorithm, called the hybrid Phasor Particle Swarm Optimization and Gravitational Search Algorithm (PPSOGSA), is proposed to solve the problem of optimal placement and sizing of inverter-based distributed generation (DG) units and shunt capacitors in radial distribution systems with linear and non-linear loads. The objective of the problem is reduction of active power losses considering constraints of the fundamental frequency active and reactive power balance, RMS voltage, and total harmonic distortion of voltage (THD_V) at each bus of the network, as well as the branch flow constraints. The performance of the PPSOGSA-based approach is evaluated on the standard IEEE 33- and 69-bus test systems under sinusoidal and non-sinusoidal operating conditions. Compared to the original PPSO and GSA and other algorithms commonly used in the optimal sitting and sizing problem of DG units and shunt capacitors, it is found that the proposed algorithm has yielded better results.

Keywords: distribution system, inverter-based distributed generation, shunt capacitor, optimal placement, harmonic distortion, hybrid optimization algorithm, phasor particle swarm optimization, gravitational search algorithm

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1. INTRODUCTION

Nowadays, the role of distribution networks becomes complex, because instead of only distributing electric energy from distribution substations to consumers, distribution networks become active with distributed generators within their borders. Distributed generation (DG) units generate electric power near load centers, reducing power transmission losses. Research studies have indicated that almost 13% of all generated electricity is wasted in the form of Joule losses at the distribution level [1]. The reduction of power losses is one of the most important goals of distribution companies. The integration of DG units in the distribution network changes the basic characteristics of the network, providing many technical, economic, and

NOMENCLATURE

$\mathbf{ac}_i(t)$	acceleration of agent i at iteration t
F	objective function
F_e	expanded objective function
G_0	initial value of the gravitational constant
$\mathbf{gbest}(t)$	the best position of all particles in the group at iteration t
h	harmonic order
$h_{\max}$	highest harmonic order
L	integer number
n	number of control variables
N	total number of agents
N_{br}	total number of branches (lines)
N_{bus}	total number of buses
N_C	number of shunt capacitors
N_{DG}	number of DG units
N_L	number of loads
P_{DGi}	active power generation of DG i
P_{grid}	substation active power injection
PL	DG penetration level
P_{Li}	active power of load i
P_{loss}	total active power losses
$P^{(h)}_{loss(i)}$	power losses of branch i at harmonic h
Q_{Ci}	reactive power injection of shunt capacitor i
$Q_C^{\min}$	minimum capacitor size
Q_{DGi}	reactive power generation of DG i
Q_{grid}	substation reactive power injection
Q_{Li}	reactive power of load i
Q_{loss}	total reactive power losses
r_1, r_2, r_3	random numbers
$S_{l,i}^{\max}$	maximum power flow in line i
t	index of iteration
$t_{\max}$	total number of iterations
$THD_V^{\max}$	maximum level of THD_V
$\mathbf{V}_i(t)$	velocity of agent i at iteration t
$V_{RMS}^{\min}$	minimum RMS bus voltage at bus i
$V_{RMS}^{\max}$	maximum RMS bus voltage at bus i
X_{Ci}	position of shunt capacitor i
X_{DGi}	position of DG i
$\mathbf{X}_i(t)$	position of agent i at iteration t
$x^{\lim}$	limit value of dependent variable x
α	user-specified constant
θ_i	phase angle of particle i
λ_V, λ_{THD}, λ_S	penalty factors

environmental benefits [2]. Some of them are reduced system losses, improved voltage profile, reliability, power quality, and system stability – as technical benefits, deferment for upgrades, reduced fuel cost and cost for reliability enhancement, less installation costs with reduced operation, and maintenance costs – as economic benefits, and reduced emission of carbon dioxide and other greenhouse gases – as environmental benefits. Further benefits may be obtained with additional installation of capacitor banks that produce reactive power. Experience has shown that, in some cases, the integration of DG units as well as capacitor banks at non-optimal locations with non-optimal sizes can lead to higher power losses, degradation of power quality, instability of the system, and escalation of operational costs. Therefore, the main priority during optimal planning of DGs and capacitors should be given to finding the best locations and sizes of DGs and capacitors for the purpose of achieve the maximum potential benefits from them. Generally, choosing the best locations for installing DG units and capacitors as well as their sizes in distribution systems with a large number of buses is a complex combinatorial optimization problem.

In recent years, many population-based optimization techniques, such as Simulated Annealing (SA), Tabu Search (TS), Genetic Algorithm (GA), Gravitational Search Algorithm (GSA), Biogeography-based Optimization (BBO), Evolutionary Programing (EP), Artificial Bee Colony (ABC), Particle Swarm Optimization (PSO), Bacterial Foraging Optimization Algorithm (BFOA), Bat Algorithm (BA), and Firefly Algorithm (FA), have been applied to find the optimal size and location of DGs and capacitor banks with different objective functions. Detailed reviews of these optimization techniques are available in the literature [3, 4]. Most of the present techniques developed for optimal DG and shunt capacitor placement and sizing problems are suited for fundamental frequency components of voltages and currents and the effects of harmonics are not taken into consideration. However, optimal solutions of the problem found under the assumption of sinusoidal condition may not be optimal due to the additional costs of harmonic power losses or high harmonic levels. The increasing presence of non-linear loads as well as DG units with renewable energy that generate harmonic currents in distribution power system has imposed a need for developing new tools and techniques, as well as adapting existing ones, in order to take the effect of harmonics into account. Some studies have shown that the presence of DG units that use power electronic converters in distribution systems can cause major problems on power quality, degradation in system reliability, and change performance of other electrical equipment [5]. The effect of DG integration on power quality of a network depends on many factors, such as the type of DG and applied converter technology. In terms of the interfacing devices to the grid, DG units can be grouped into two categories [6]: (i) inverter-based DG, such as PV systems, wind turbine generators, fuel cells, and micro turbines and (ii) non-inverter-based DG, like mini-hydro synchronous generators and induction generators. One of the most important aspects of power quality is the presence of harmonics. Harmonics are mainly caused by non-linear loads like adjustable speed drives and power conversion devices. In addition to non-linear loads, the increasing use of inverter-based DG resources in the last few years has caused the increased emergence of harmonics in distribution networks.

In the literature, there are few documents that have considered the effect of harmonics on optimal placement and sizing of DGs and/or capacitor banks [7–14]. In [7], BBO method is applied to find the optimal location and sizing of solar photovoltaic DG units with intent to minimize power losses and improve voltage profile, while total harmonic distortion of voltage (THD_V) and individual harmonic distortion of voltage (IHD_V) are maintained within harmonic distortion standard limits. Also in [8], BBO is employed for the simultaneous placement of non-inverter-based DG units and capacitor banks in distribution networks with non-linear loads in order to reduce the active and reactive power losses and to take into account the value reduction of losses at different load levels. The optimal location and sizing of shunt capacitor banks in the presence of non-linear loads and inverter-based distributed generation sources using PSO was studied in [9]. There, the objective function is composed of three parts: maximizing annual profit of capacitor installation, minimizing total harmonic distortion, and minimizing bus voltage deviation from the nominal voltage (1.0 p.u.). In [10], a Global Harmony Search algorithm (GHS) is employed for the solution of optimal placement and sizing of capacitors in radial distribution networks with an objective function that reflects reductions of the total power loss and total cost by taking account load unbalancing, mutual coupling and harmonics. Authors in [11] have used an improved GSA for optimal placement and sizing of renewable DGs in a distribution system. In that work, the objective function was to minimize losses, THDv levels, and voltage deviation. Seyed *et al*. [12] proposed the application of GA for optimal capacitor placement and sizing in radial distribution networks with non-linear loads and inverter-based DG units, with the objective of maximizing the net saving and minimizing power losses. In another research by Heydari *et al*. [13], the optimal location and size of shunt capacitors and non-inverter-based DG units in distorted radial distribution systems were determined by the discrete PSO algorithm. The same planning problem, but with considering inverter-based DG units instead non-inverter-based DG units, authors in [14] have solved by BBO.

In this paper, a hybrid algorithm based on the Phasor Particle Swarm Optimization (PPSO) [15] and Gravitational Search Algorithm (GSA) [16], named hybrid PPSOGSA, is proposed to solve the optimal placement and sizing problem of inverter-based DG units and shunt capacitor banks in distribution systems with linear and non-linear loads. The constraints of the considered problem include different limits, such as the fundamental frequency active and reactive power balance, RMS voltage, and THD_V limits. The proposed method is tested on the IEEE 33- and 69-bus test systems under sinusoidal and non-sinusoidal operating conditions for the purpose of active power losses minimization. The results obtained by the proposed method were compared with those obtained using the original PPSO and GSA methods and those reported in the literature.

2. PROBLEM FORMULATION

The problem of optimal placement and sizing of DGs and shunt capacitors is considered as a non-linear combinatorial optimization planning problem with the objective of minimizing the total active power losses in the system and bring the bus voltages and total harmonic distortions within the limits defined by the IEEE-519 standard [17]. The total active power losses are given by:

$$P_{loss} = \sum_{h=1}^{h_{\max}} \left(\sum_{i=1}^{N_{br}} P_{loss(i)}^{(h)} \right) \tag{1}$$

where P_{loss} is the total active power losses in the system, $P_{loss(i)}^{(h)}$ is the power losses of the ith branch at the hth harmonic, N_{br} is the total number of branches (lines), and $h_{\max}$ is the maximum harmonic order under consideration.

The objective function is defined as:

$$F = \min(P_{loss}) \tag{2}$$

This objective function is subject to the equality and inequality constraints.

Equality constraints:

Power balance constraints at the fundamental frequency:

$$P_{grid} + \sum_{i=1}^{N_{DG}} P_{DGi} = \sum_{i=1}^{N_{br}} P_{loss(i)}^{(1)} + \sum_{i=1}^{N_L} P_{Li} \tag{3}$$

$$Q_{grid} + \sum_{i=1}^{N_{DG}} Q_{DGi} + \sum_{i=1}^{N_C} Q_{Ci} = \sum_{i=1}^{N_{br}} Q_{loss(i)}^{(1)} + \sum_{i=1}^{N_L} Q_{Li} \tag{4}$$

where P_{grid} and Q_{grid} are the substation active and reactive power injections, P_{DGi} and Q_{DGi} are the active and reactive power generations of the ith DG, Q_{Ci} is the reactive power injection of the ith shunt capacitor, $P_{loss(i)}^{(1)}$ and $Q_{loss(i)}^{(1)}$ are

Step 1	Search space identification. Initialize PPSOGSA parameters: total number of agents (N), total number of iterations ($t_{\max}$), initial value of the gravitational constant (G_0), and user-specified constant (α).
Step 2	Initialization: Randomly generate an initial population of N agents with their own phase angle through uniform distribution $\theta_i(0)=U(0, 2\pi)$, and with initial velocity within the velocity bound. The initial positions of each agent are randomly selected between the minimum and maximum values of the control variables.
Step 3	Set the index of iteration $t=1$.
Step 4	For each particle in the population, run BFS power flow and DHPF to obtain the power losses, bus RMS voltages and THD_V values.
Step 5	Calculate the fitness value for each agent.
Step 6	Update the velocity and position of all agents by (15) and (16), respectively.
Step 7	If the stop criteria is satisfied (*i.e.*, the maximum number of iterations is reached), go to step 8; otherwise, set iteration index $t = t+1$, and return to step 4.
Step 8	Return the best solution found. Print out the optimal solution to the problem. Stop.

TABLE 1. Steps of the proposed hybrid PPSOGSA algorithm.

the fundamental active and reactive power losses of the ith branch, P_{Li} and Q_{Li} are the active and reactive powers of the load at bus i, while N_{DG}, N_C, and N_L are the number of DG units, number of shunt capacitors, and number of loads, respectively. The Backward-Forward Sweep (BFS) method [18] was used to obtain parameters of the system at the fundamental frequency.

Constrains related to the harmonic power flow:

$$\mathbf{V}^{(h)} = \left[\mathbf{Y}_{\mathbf{BUS}}^{(h)}\right]^{-1}\mathbf{I}^{(h)} \tag{5}$$

where $\mathbf{V}^{(h)}$ is the system bus voltage vector at the hth harmonic, $\mathbf{I}^{(h)}$ is the system bus injected current vector at the hth harmonic, and $\mathbf{Y}_{\mathbf{BUS}}^{(h)}$ is the system bus admittance matrix at the hth harmonic.

Inequality constraints:

Bus voltage constraints:

$$V_{RMS}^{\min} \le \sqrt{\sum_{h=1}^{h_{\max}} \left|\underline{V}_i^{(h)}\right|^2} \le V_{RMS}^{\max}, \qquad i = 1, 2, ..., N_{bus} \tag{6}$$

where $V_{RMS}^{\min} = 0.95$ p.u. and $V_{RMS}^{\max} = 1.05$ p.u. are the minimum and maximum RMS bus voltage limits at bus i, respectively.

Total harmonic distortion of voltage constraints:

$$THD_{V,i}(\%) = \frac{1}{\left|\underline{V}_i^{(1)}\right|} \cdot \sqrt{\sum_{h\neq 1}^{h_{max}} \left|\underline{V}_i^{(h)}\right|^2} \times 100(\%) \le THD_V^{\max}, \qquad i = 1, 2, ..., N_{bus} \tag{7}$$

where $THD_V^{\max} = 5\%$ is the maximum acceptable level of the THD_V, according to the IEEE-519 standard [17]. Harmonic components are estimated using the Decoupled Harmonic Power Flow (DHPF) algorithm [19, 20].

Branch flow constraints:

$$S_{l,i} \le S_{l,i}^{\max}, \qquad i = 1, ..., N_L \tag{8}$$

where $S_{l,i}^{\max}$ is the maximum power flow in line i.

Constraints on control variables:

Distributed generation capacity constraints:

$$\sum_{i=1}^{N_{DG}} \sqrt{P_{DGi}^2 + Q_{DGi}^2} \le PL \sum_{i=1}^{N_L} \sqrt{P_{Li}^2 + Q_{Li}^2} \tag{9}$$

where PL is the DG penetration level in percent.

In this paper, the inverter-based DG units are modeled as negative loads with unity power factor (produce only active power), as recommended by the IEEE 1547 standard [21].

Capacitor capacity constraints:

$$\sum_{i=1}^{N_C} Q_{Ci} \le \sum_{i=1}^{N_L} Q_{Li} \tag{10}$$

Capacitor sizes are taken as discrete variables in order to deal with practical cases, *i.e.*

$$Q_{Ci} = LQ_C^{\min} \tag{11}$$

where L is an integer number and $Q_C^{\min}$ is the smallest capacitor size, considered to be 150 kVAr.

Distributed generation and capacitor positions constraints:

$$2 \le X_{DGi} \le N_{bus} \tag{12}$$

$$2 \le X_{Ci} \le N_{bus} \tag{13}$$

where X_{DGi}, X_{Ci}, and N_{bus} represent the position of the ith DG, the position of the ith shunt capacitor, and the total

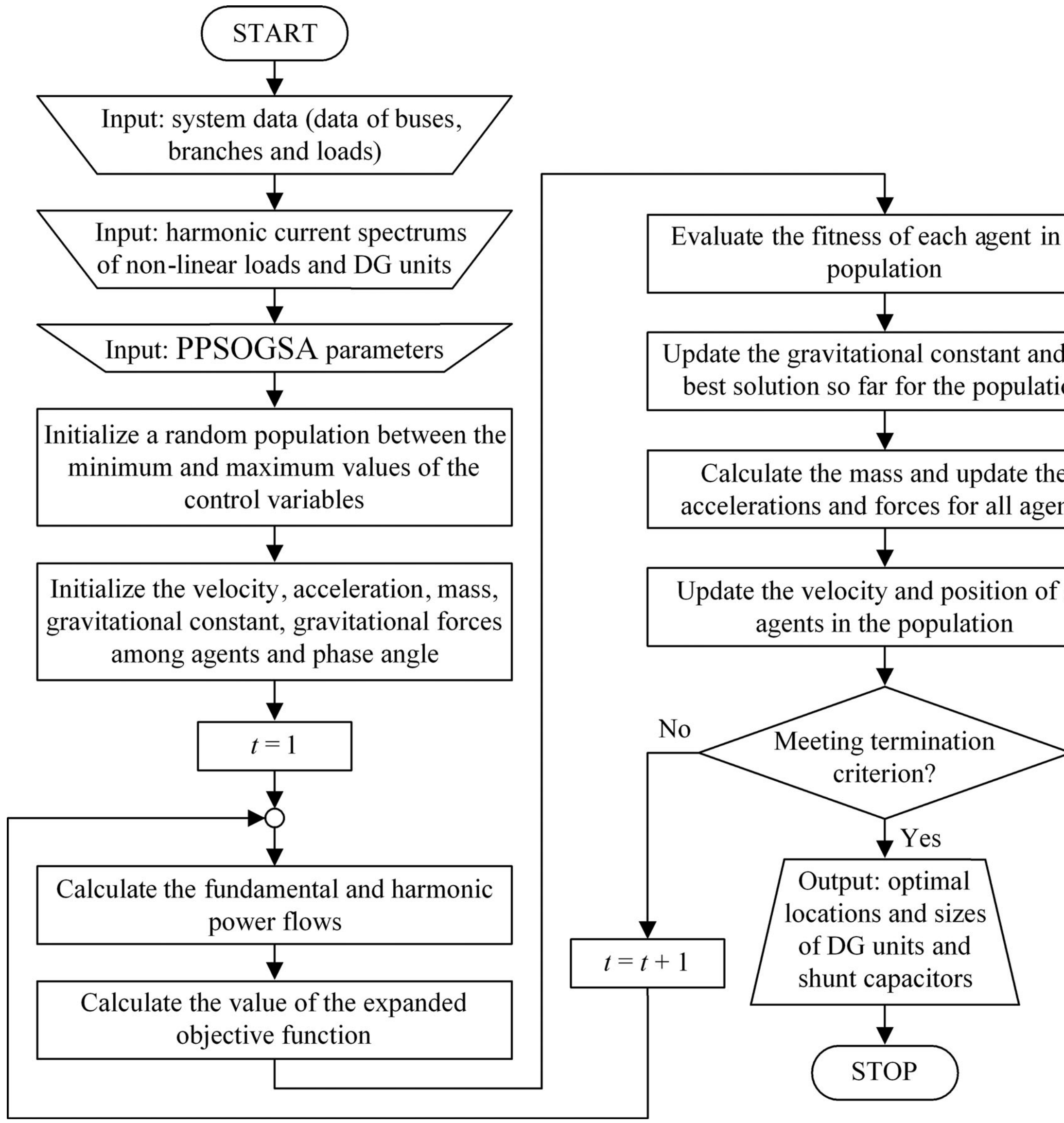

FIGURE 1. Flowchart illustrating the PPSOGSA-based approach to optimizing the locations and sizes of DG units and capacitor banks.

number of buses in the system, respectively. So, all buses of the system, except the power supply bus 1, are considered as potential locations for placement of DGs and capacitors.

It is important to note that the control variables are self-constrained, but dependent variables (*i.e.*, RMS bus voltages, THD_V levels, and branch loadings) are not. The inequality constraints of dependent variables are incorporated in the objective function as quadratic penalty factors. Therefore, the new expanded objective function to be minimized becomes:

$$F_e = F + \lambda_V \sum_{i=1}^{N_{bus}} \left(V_{RMS,i} - V_{RMS,i}^{\lim} \right)^2 + \lambda_{THD} \sum_{i=1}^{N_{bus}} \left(THD_{V,i} - THD_{V,i}^{\lim} \right)^2 + \lambda_S \sum_{i=1}^{N_{br}} \left(S_{l,i} - S_{l,i}^{\lim} \right)^2 \quad (14)$$

where F_e is the expanded objective function, λ_V, λ_{THD}, and λ_S are defined as penalty factors; $x^{\lim}$ is the limit value of dependent variable x, which is given by: $x^{\lim} = x^{\max}$ if

$x > x^{max}$ and $x^{lim} = x^{min}$ if $x < x^{min}$. In this study, the penalty factor of 10^6 is selected for all the inequality constraints.

2.1. Assumptions

Several practical assumptions which are necessary for the proper formulation of the problem have been adopted:

- The distribution system is symmetrical and balanced.
- Line and cable capacitance are neglected.
- There are no geographic or primary resource limitations to install inverter-based DG units within the distribution system.
- Voltage at the primary bus of a substation is 1.0 p.u.
- The substation voltage does not contain any harmonic component.
- All buses of the system, except the power supply bus 1, are considered as potential locations for placement of inverter-based DGs and shunt capacitors.
- Only one inverter-based DG can be connected to the same bus in the distribution system.
- Only one shunt capacitor can be connected to the same bus in the distribution system.
- All inverter-based DG units are modeled as negative loads with unity power factor – produce active power only, as recommended by the IEEE 1547 standard.
- At the fundamental frequency, all loads are represented as constant PQ loads, while capacitors are represented as constant impedances.
- At the harmonic frequencies, linear loads are represented by the parallel RL impedance model, and non-linear loads are treated as decoupled harmonic current sources that inject harmonic currents in the system.

3. THE HYBRID PPSOGSA ALGORITHM

The proposed PPSOGSA algorithm, in a similar way as the PSOGSA algorithm [22], hybridizes PPSO [15] with GSA [16] by combining the ability for social thinking (**gbest**) in PPSO with the local search capability of GSA. The main improvement of PPSOGSA in relation to PSOGSA is based on modeling the particle control parameters with a phase angle (θ) transforming the standard PSO algorithm to a self-adaptive and parametric independent algorithm. The particle control parameters of PSOGSA c_1 and c_2 are fixed during iteration process and different combination values of these parameters provide good solutions for different problems. Instead of using fixed value of c_1 and c_2, in this new hybrid algorithm the periodic nature of trigonometric sine and cosine functions is utilized to represent the control parameters through phase angles. By doing this, the velocity and position of the ith particle in each of iteration are updated using the following equations:

Control parameters	PPSO	GSA	PPSOGSA
Population size (N)	50	50	50
Maximum number of iterations (t_{max})	200	200	200
Initial value of the gravitational constant (G_0)	–	100	20
User-specified constant (α)	–	2	20

TABLE 2. Parameter setting used in PPSO, GSA, and PPSOGSA.

Harmonic order	Magnitude (%)			
	Non-linear loads			
	Six-pulse type 1 connected at bus 6	Six-pulse type 2 connected at bus 18	Six-pulse type 3 connected at bus 30	Inverter-based DGs
1	100	100	100	100
5	20	19.1	42	4
7	14.3	13.1	14.3	4
11	9.1	7.2	7.9	2
13	7.7	5.6	3.2	2
17	5.9	3.3	3.7	1.5
19	5.3	2.4	2.3	1.5
23	4.3	1.2	2.3	0.6
25	4	0.8	1.4	0.6
29	3.4	0.2	0	0.6
31	3.2	0.2	0	0.6

TABLE 3. The harmonic spectrums of non-linear loads and DG units.

$$\mathbf{V}_i(t+1) = r_1\mathbf{V}_i(t) + r_2|\cos(\theta_i(t))|^{2\sin(\theta_i(t))}\mathbf{ac}_i(t) + r_3|\sin(\theta_i(t))|^{2\cos(\theta_i(t))}(\mathbf{gbest}(t) - \mathbf{X}_i(t)) \quad (15)$$

$$\mathbf{X}_i(t+1) = \mathbf{X}_i(t) + \mathbf{V}_i(t+1) \quad (16)$$

where the phase angle of particle i (θ_i) is calculated for the next iteration through the following formula:

$$\theta_i(t+1) = \theta_i(t) + |\cos(\theta_i(t)) + \sin(\theta_i(t))|2\pi \quad (17)$$

In Eqs. (15)–(17), variables have the following meaning: $i = 1, \ldots, N$ is the agent number; $\mathbf{V}_i(t)$ and $\mathbf{X}_i(t)$ are the velocity and the position of agent i at iteration t, respectively; r_1, r_2, and r_3 are random numbers between 0 and 1; $\mathbf{ac}_i(t)$ is the acceleration of agent i at iteration t; and $\mathbf{gbest}(t)$ is the best position of all particles in the group at iteration t. The values of $\mathbf{ac}_i$ and $\mathbf{gbest}$ in Eq. (15) are obtained as in [22].

Case	Method	DG size in MW and location	Capacitor size in MVAr and location	Minimum voltage (p.u.)	Power losses (kW)	Losses reduction (%)
Base case	–	–	–	0.9038	210.9983	–
Case 1	PPSOGSA	2.5274 (6)	1.35 (30)	0.9542	58.5913	72.23
	PPSO	2.5274 (6)	1.35 (30)	0.9542	58.5913	72.23
	GSA	2.5274 (6)	1.35 (30)	0.9542	58.5913	72.23
	PSO [26]	2.5106 (6)	1.4571 (30)	0.955	59.7	71.7
	LSF-based [24]	2.543 (6)	1.4 (28)	0.9582	62.97	70.15
	HAS-PABC [24]	2.531 (6)	1.25 (30)	0.9583	58.45	72.29
Case 2	PPSOGSA	0.8461 (13)	0.45 (12)	0.9804	28.4956	86.49
		1.1371 (30)	1.05 (30)			
	PPSO	0.846 (13)	0.75 (8)	0.9807	29.8239	85.87
		1.1379 (30)	0.9 (30)			
	GSA	0.8454 (13)	0.6 (9)	0.9806	29.2912	86.12
		1.133 (30)	1.05 (30)			
	IMDE [27]	1.08 (10)	0.2548 (16)	0.979	32.08	84.79
		0.8964 (31)	0.9323 (30)			
	Analytical approach [28]	0.447 (18)	0.4 (33)	0.9611	84.28	60.05
		0.5590 (17)	0.5 (32)			
	MOEA/D [25]	0.84 (13)	0.453 (12)	0.98	28.47	86.51
		1.14 (30)	1.04 (30)			
Case 3	PPSOGSA	0.7655 (14)	0.3 (14)	0.9906	11.9966	94.31
		1.0747 (24)	0.6 (24)			
		1.0411 (30)	1.05 (30)			
	PPSO	0.7943 (13)	0.45 (12)	0.9923	13.1643	93.76
		1.0705 (24)	0.15 (25)			
		1.0284 (30)	1.05 (30)			
	GSA	0.7667 (14)	0.3 (14)	0.9896	12.9643	93.86
		1.0744 (24)	0.75 (25)			
		1.0477 (30)	0.9 (30)			
	BFOA [29]	0.542 (17)	0.163 (18)	0.9783	41.41	80.37
		0.16 (18)	0.541 (30)			
		0.895 (33)	0.338 (33)			
	GA [30]	0.4937 (8)	0.45 (6)	0.9862	16.41	92.22
		0.4953 (14)	0.45 (12)			
		0.4953 (25)	0.75 (33)			

TABLE 4. Simulation results of the IEEE 33-bus test system under the sinusoidal operating condition.

3.1. PPSOGSA Implementation

The control variables of the optimal placement and sizing problem of inverter-based DG units and shunt capacitors constitute the individual position of several agents that represent a complete solution set. In this case, a potential solution can be presented by a vector consisting of a combination of locations of DG units and shunt capacitors and their rated powers. Accordingly, the *i*th agent can be written as follows:

$$\mathbf{X}_i = \left[X_{DG1}^{1}, \ldots, X_{DGN_{DG}}^{d}, P_{DG1}^{d+1}, \ldots, P_{DGN_{DG}}^{2d}, X_{C1}^{2d+1}, \ldots, X_{CN_C}^{3d}, Q_{C1}^{3d+1}, \ldots, Q_{CN_C}^{n}\right] \quad (18)$$

where $n = 2N_{DG} + 2N_C$ denotes the number of control variables.

The different steps of the PPSOGSA approach for the considered optimization problem are listed in Table 1. The flowchart in Figure 1 illustrates the proposed PPSOGSA approach to optimizing the locations and sizes of DG units and capacitor banks.

The computer program was developed in the MATLAB R2017b computing environment and run on a 2.70-GHz PC with 8 GB RAM. In order to examine the efficiency of the proposed technique in solving the problem of optimal location and size of DG units and capacitors, the same problem was solved using PPSO and GSA, and the results are compared to those obtained using other techniques reported in the literature. The setting parameters of PPSO, GSA, and PPSOGSA used in calculations are provided in Table 2. Twenty consecutive test runs have been performed and results presented here are the best values obtained over these runs.

4. RESULTS AND DISCUSSION

4.1. Simulations on the IEEE 33-Bus Test System

The proposed hybrid PPSOGSA algorithm is tested on the IEEE 33-bus radial distribution test system [23] with the total active and reactive power demands of 3.715 MW and 2.3 MVAr, respectively. The base voltage and base power of this system are 12.66 kV and 10 MVA. The limits of shunt capacitor sizes and DG sizes are assumed to be from 0 to 2.25 MVAr, and from 0 to 3.5 MW, respectively. Both the sinusoidal and non-sinusoidal operating conditions were taken into account. To investigate the impact of non-linear loads on the power quality of the distribution system, it is assumed that the loads connected at buses 6, 18, and 30 are six-pulse diode rectifiers. In addition to this, inverter-based DG units are treated as negative non-linear loads. The harmonic spectrum of the current injected by DG units is considered to be the upper bound of the individual harmonic current limits specified by the IEEE-1547 standard [21], and only contains non-triplen odd-order harmonic components. The typical harmonic spectrums of the non-linear loads [20] and inverter-based DGs [21] are presented in Table 3. Harmonic phase angles are assumed to be zero.

In addition to the basic case (*i.e.*, the case without any DG and capacitor), the following cases are analyzed:

Case 1: With one DG and one shunt capacitor.

Case 2: With two DGs and two shunt capacitors.

Case 3: With three DGs and three shunt capacitors.

4.1.1. Sinusoidal Operating Condition. Under the sinusoidal operating condition all loads as well as DG units are treated as linear and the calculations are carried out only at the fundamental frequency (*i.e.*, 50 Hz). Results of the optimal sizing and sitting of DGs and capacitors are shown in Table 4. Table 4 also contains results obtained by other optimization techniques.

Before the placement of DGs and capacitors, the total active power losses of the system are 210.9983 kW and the minimum voltage is 0.9038 p.u. For Case 1, the PPSOGSA, PPSO, and GSA produce the same solution, whereas for Case 2 and Case 3 optimal solutions obtained by PPSOGSA are better than those obtained using PPSO and GSA. By comparing the results from Table 4, it can be

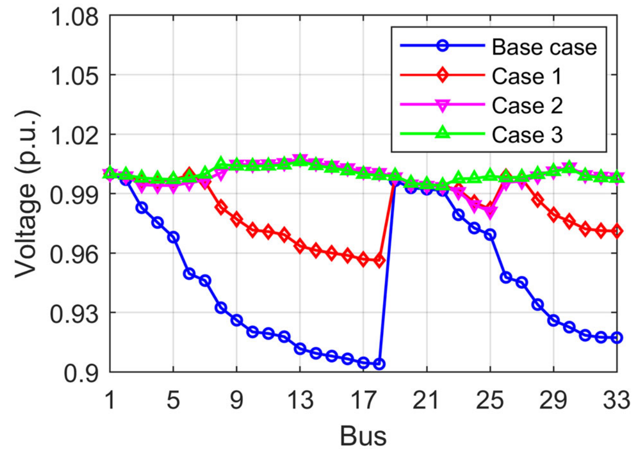

FIGURE 2. Comparison of voltage profiles for different cases under the sinusoidal operating condition.

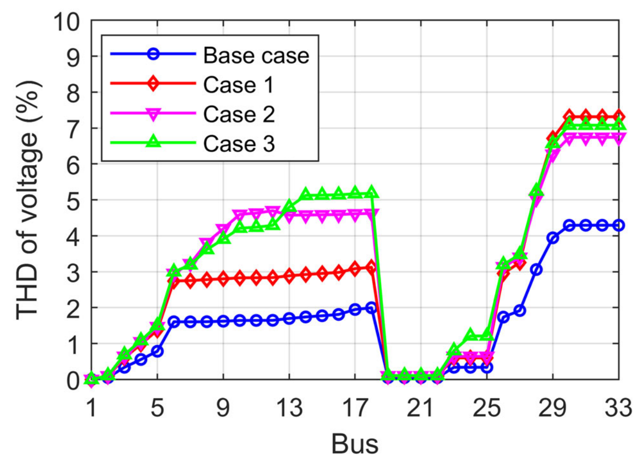

FIGURE 3. Comparison of THD_V levels for the base non-sinusoidal case and cases when the parameters of DG units and capacitors are obtained by PPSOGSA under the sinusoidal operation condition.

seen that the losses obtained with the proposed PPSOGSA are lower than those obtained by other methods, except HAS-PABC [24] and MOEA/D [25] methods. In [24], the step size of one fixed capacitor unit was 50 kVAr, while in [25] capacitor sizes are taken as continuous variables; that may be a possible reason why the losses from [24] and [25] are less than those obtained by PPSOGSA. Also, the results from the eight column of the table show that the reduction of losses is more expressed with increasing the number of DG units and capacitors at different locations in the system.

By connecting DG units and shunt capacitors to the distribution network, the network becomes active, resulting in a change in the direction of active and reactive power

Case	Method	DG size in MW and location	Capacitor size in MVAr and location	Maximum THD_V (%)	Minimum RMS voltage (p.u.)	Power losses (kW)	Losses reduction (%)
Base case	–	–	–	4.2928	0.904	213.8196	–
Case 1	PPSOGSA	2.5326 (6)	1.5 (27)	4.9167	0.9563	72.8503	65.93
	PPSO	2.5326 (6)	1.5 (27)	4.9167	0.9563	72.8503	65.93
	GSA	2.4062 (26)	1.65 (6)	4.5536	0.9559	74.8869	64.98
Case 2	PPSOGSA	0.8423 (13)	0.9 (9)	4.9862	0.981	39.9226	81.33
		1.1503 (30)	0.9 (30)				
	PPSO	0.8444 (13)	0.6 (10)	4.8829	0.9807	41.3022	80.68
		1.1525 (30)	1.05 (28)				
	GSA	0.8411 (13)	0.6 (3)	4.3729	0.9814	48.8468	77.16
		1.1558 (30)	1.5 (6)				
Case 3	PPSOGSA	0.8063 (13)	1.05 (8)	4.9126	0.9939	25.8001	87.93
		0.8023 (25)	0.45 (24)				
		1.0901 (30)	0.75 (30)				
	PPSO	0.7603 (14)	0.75 (10)	4.8797	0.9941	27.7403	87.03
		1.0608 (24)	0.3 (25)				
		1.0548 (30)	1.2 (29)				
	GSA	1.6175 (3)	0.75 (4)	4.9883	0.9864	31.6376	85.21
		0.7532 (13)	0.6 (16)				
		1.0098 (30)	0.6 (30)				

TABLE 5. Simulation results of the IEEE 33-bus system under the non-sinusoidal operating condition.

flows in the network. This change in power flows leads to a change in voltage drops across power lines from the power supply bus to the peripheral parts of the network and, consequently, bus voltages. The comparison of voltage profiles for the analyzed cases is illustrated in Figure 2. It is evident that the voltage profile is significantly improved after the installation of the capacitors and DG resources, where the voltage magnitude at each bus is within permissible limits. The best voltage profile of the network, *i.e.*, the minimum voltage deviation from the nominal voltage (1.0 p.u.), is obtained in Case 3. This is expected, because in Case 3 the number of DG units and shunt capacitors is highest.

4.1.2. Non-Sinusoidal Operating Condition. In some cases, the size and location of inverter-based DGs and capacitors can influence on the level of harmonic distortion in the whole system. In order to demonstrate the effect of installation of inverter-based DGs and shunt capacitors on the harmonic distortion of the system, calculations of the harmonic power flow were performed. THD_V at all buses of the system in the base non-sinusoidal case (*i.e.*, the case without any inverter-based DG and capacitor, but with the non-linear loads instead of the linear loads) and cases when the parameters of all DG units and capacitors are obtained by PPSOGSA under the sinusoidal operation condition are shown in Figure 3. Before optimization, total active power losses of the system are 213.8196 kW of which 2.8213 kW represents the losses caused by the harmonics resulting from non-linear loads, while the maximum THD_V level is 4.2928%.

As can be seen from Figure 3, after optimization THD_V values at buses 28 to 33 reaches the level higher than allowable level of 5%. In relation to the base non-sinusoidal case, the maximum value of THD_V for Cases 1, 2, and 3 increases by 70.36%, 57.06%, and 64.9%, respectively. This increase in voltage distortion level is due to the additional harmonic currents generated by DG units and harmonic resonant conditions caused by capacitors in combination with load and feeder reactances. Based on that, it can be said that the solutions of the optimal placement and sizing of DGs and capacitors found for sinusoidal operation condition, in the presence of harmonics, are not acceptable.

To show the performance of the proposed algorithm under non-sinusoidal operating condition, the non-linear nature of the inverter-based DG units and loads is taken into account and the best optimal results for three different cases are given in Table 5. From these results, it is evident that the minimum RMS voltages and the maximum THD_V levels do not violate the permissible limits in all cases where the optimization is performed. Also, it can be seen

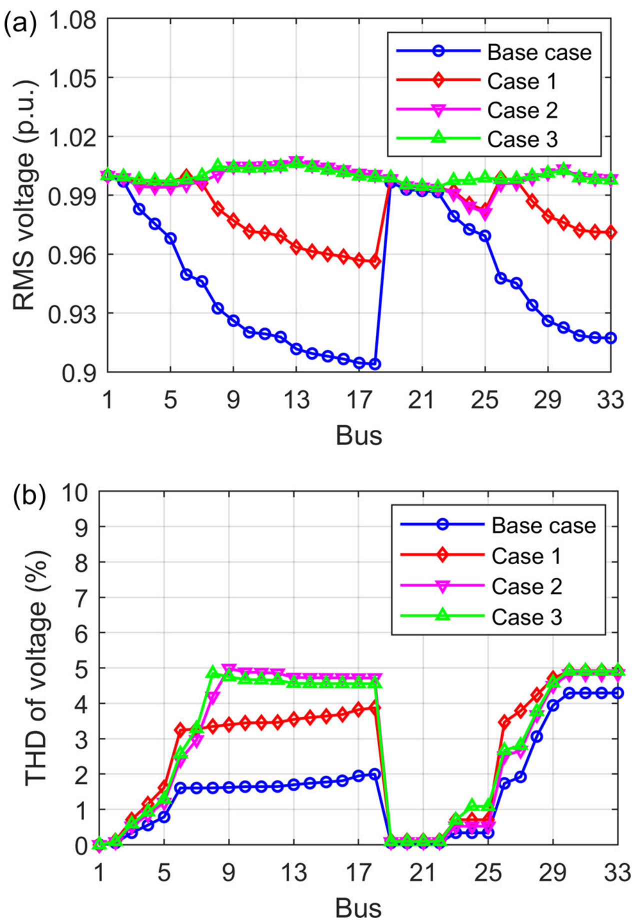

FIGURE 4. Comparisons (a) between voltage profiles and (b) THD_V levels for the base non-sinusoidal case and cases when the parameters of DG units and capacitors are obtained by the PPSOGSA algorithm.

that the proposed PPSOGSA method leads to the greatest reduction in active power losses in all considered cases, which confirms its excellent performances in solving the optimal placement and sizing problem of DGs and shunt capacitors. Compared to the base non-linear case, the best solutions generated by PPSOGSA provide reductions of 65.93%, 81.33%, and 87.93% in power losses for Cases 1, 2, and 3, respectively.

Figures 4(a) and 4(b), respectively, illustrate the comparisons between RMS voltage profiles and THD_V levels for cases without and with capacitors and DG resources obtained by the PPSOGSA algorithm. After installing DG units and shunt capacitors, the power flows from the power supply bus to the load buses are reduced, and, consequently, the voltage profiles are improved, as can be seen from Figure 4(a). In addition, due to the harmonic currents generated by DG units and resonant conditions caused by capacitors in combination with load and feeder reactances, there is an increase in voltage distortion level at all busses of the network, as can be observed from Figure 4(b). However, the maximum THD_V levels meet the permissible limit of 5% for all optimization cases.

4.1.3. Statistical Parameters and Convergence Profiles. In order to evaluate the performance metrics (minimum, maximum, average, and standard deviation) of PPSO, GSA, and PPSOGSA algorithms, each algorithm is executed 20 times for each case. The statistic comparison results of performance metrics for the IEEE 33-bus test system under sinusoidal and non-sinusoidal operating conditions are shown in Table 6. It is clear that the proposed algorithm has better performance in comparison to the original PPSO and GSA.

The convergence characteristics of one run of the algorithms for Case 3 under sinusoidal and non-sinusoidal operation conditions are illustrated in Figures 5(a) and 5(b). From these figures it may be observed that the proposed PPSOGSA tends to find the optimal solution faster than the original PPSO and GSA. In addition, the authors have been performed several test runs and, depending on the number of control variables (*i.e.*, the number of DG units and shunt capacitors), it was found that the proposed algorithm converges to the final solution after 10–50 iterations. From the aspect of running, the running time of PPSOGSA algorithm is slightly longer than the running time of other algorithms. The average running time of one iteration for the hybrid PPSOGSA algorithm in Case 3 under the sinusoidal condition was about 20 s, while under the non-sinusoidal condition it was about 2 min.

4.2. Simulations on the IEEE 69-Bus Test System

In order to evaluate the efficiency of the proposed PPSOGSA approach in solving a larger power system, the IEEE 69-bus test system [31] is considered. The total active and reactive powers of the system are 3.792 MW and 2.694 MVAr, respectively. The limits of shunt capacitor sizes and DG sizes are assumed to be from 0 to 2.55 MVAr, and from 0 to 3.72 MW, respectively. As in the previous testing system, both the sinusoidal and non-sinusoidal operating conditions were taken into account.

4.2.1. Sinusoidal Operating Condition. The solutions are obtained for the optimal placement and sizing of three DG units and three shunt capacitors, as in Case 3 for the IEEE 33-bus test system. The simulation results, obtained using the proposed PPSOGSA as well as PPSO and GSA, are compared with those obtained using the IPSO and MOEA/

Operating condition	Case	Method	Min (kW)	Max (kW)	Mean (kW)	Std. dev. (kW)
Sinusoidal	1	PPSO	58.5913	60.3808	58.7702	0.5659
		GSA	58.5913	69.5936	61.6551	4.5855
		PPSOGSA	58.5913	59.5865	58.6908	0.3147
	2	PPSO	29.8239	38.8454	31.8603	3.0904
		GSA	29.2912	55.7542	40.2113	7.8763
		PPSOGSA	28.4956	32.0840	29.2058	1.2743
	3	PPSO	13.1643	25.7888	18.5602	4.7849
		GSA	12.9643	56.4574	32.7168	15.2734
		PPSOGSA	11.9966	17.0135	14.4371	2.2021
Non-sinusoidal	1	PPSO	72.8503	75.1809	73.9130	1.1003
		GSA	74.8869	76.9346	74.2967	1.8436
		PPSOGSA	72.8503	74.2324	73.2427	0.4029
	2	PPSO	41.3022	46.1186	45.7183	4.1205
		GSA	48.8468	60.9363	51.8589	4.3176
		PPSOGSA	39.9226	45.7221	42.5815	3.7892
	3	PPSO	27.7403	47.1589	31.4391	6.1915
		GSA	31.6376	61.8884	46.4522	9.5177
		PPSOGSA	25.8001	41.9151	31.3285	5.9923

TABLE 6. Statistical parameters of PPSO, GSA, and PPSOGSA.

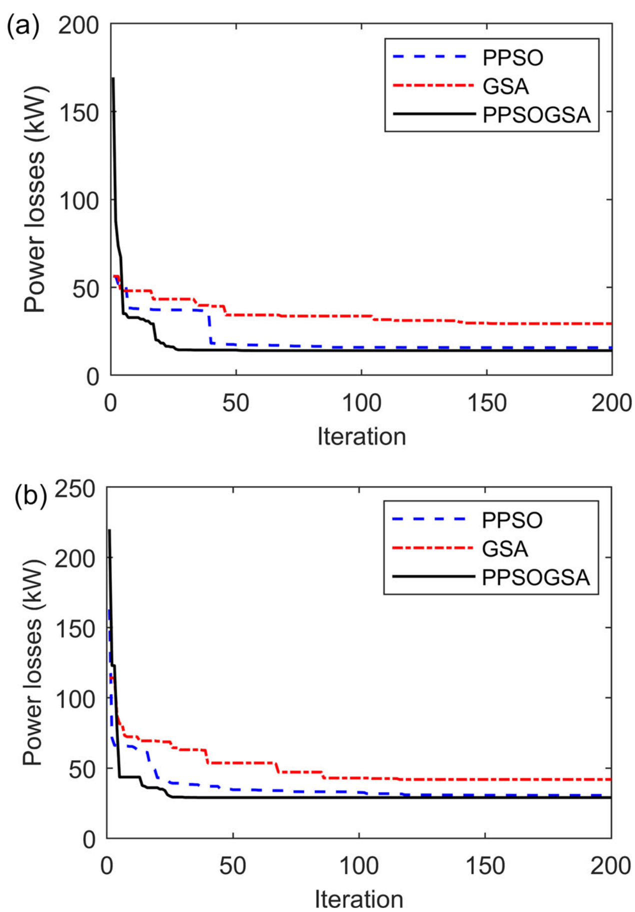

FIGURE 5. Convergence profiles of PPSO, GSA, and PPSOGSA for Case 3 under (a) sinusoidal operating condition and (b) non-sinusoidal operating condition.

D algorithms, as shown in Table 7. Compared to the base power losses of 224.948 kW, the total power losses obtained by the PPSOGSA are reduced to 4.3211 kW. It can be seen that the losses obtained with the proposed PPSOGSA are lower than those obtained by other algorithms, except the MOEA/D [25] algorithm. In [25], the capacitor sizes are taken as continuous variables; that may be a possible reason why the losses from [25] are less than those obtained by PPSOGSA.

4.2.2. Non-Sinusoidal Operating Condition. To investigate the impact of non-linear loads on the power quality of the system, it is assumed that the load connected at bus 61 is the six-pulse diode rectifier type 2. The harmonic current magnitudes used to model the six-pulse rectifier are identical to those presented in Table 3. First of all, the calculation of the harmonic power flow was performed for the base non-sinusoidal case (*i.e.*, the case without any inverter-based DG and capacitor, but with the non-linear load instead of the linear load). The results are presented in Table 8. As can be seen in the base case, the total active power losses of the system are 230.789 kW of which 5.841 kW represents the losses caused by the harmonics, and the maximum THD_V level is 4.9895%. After that, the harmonic power flow was performed for the case when the locations and sizes of DG units and capacitors are obtained by PPSOGSA under the sinusoidal operation condition. In that case, the maximum THD_V level occurs at bus 61 and reaches a value of 6.77%. According to this, it is clear that the solution of the optimal placement and sizing of DGs

Case	Method	DG size in MW and location	Capacitor size in MVAr and location	Minimum voltage (p.u.)	Power losses (kW)	Losses reduction (%)
Base case	–	–	–	0.9092	224.948	–
Three DG units and three shunt capacitors (Case 3)	PPSOGSA	0.4944 (11) 0.3781 (18) 1.6741 (61)	0.3 (11) 0.3 (18) 1.2 (61)	0.9943	4.3211	98.08
	PPSO	0.4174 (17) 1.7326 (61) 0.4117 (67)	0.3 (18) 0.45 (50) 1.2 (61)	0.9971	4.9837	97.78
	GSA	0.4676 (17) 0.5405 (51) 1.6389 (61)	0.45 (12) 0.15 (21) 1.2 (61)	0.9943	5.2241	97.68
	MOEA/D [25]	0.495 (11) 0.379 (18) 1.675 (61)	0.375 (11) 0.23 (21) 1.196 (61)	0.9943	4.25	98.11
	IPSO [25]	0.557 (11) 0.321 (21) 1.672 (61)	0.3 (11) 0.3 (18) 1.2 (61)	0.9943	4.37	98.06

TABLE 7. Simulation results of the IEEE 69-bus test system under the sinusoidal operating condition.

Case	Method	DG size in MW and location	Capacitor size in MVAr and location	Maximum THD_V (%)	Minimum RMS voltage (p.u.)	Power losses (kW)	Losses reduction (%)
Base case	–	–	–	4.9895	0.9103	230.789	–
Three DG units and three shunt capacitors (Case 3)	PPSOGSA	0.6012 (11) 0.3609 (18) 1.6661 (61)	0.3 (18) 0.6 (50) 1.5 (56)	4.8644	0.9939	45.985	80.07
	PPSO	0.4883 (18) 0.7869 (53) 1.6004 (61)	0.3 (12) 0.15 (21) 1.35 (56)	4.9037	0.9891	47.2448	79.53
	GSA	0.4951 (19) 1.2504 (49) 1.7067 (61)	0.3 (19) 0.15 (55) 1.35 (56)	4.8642	0.9875	47.8346	79.27

TABLE 8. Simulation results of the IEEE 69-bus system under the non-sinusoidal operating condition.

and capacitors found for the sinusoidal operation condition, in the presence of harmonics, is not acceptable.

The results obtained using the PPSOGSA, PPSO, and GSA algorithms for the non-sinusoidal operating condition are listed in Table 8. On the basis of these results, it is evident that the minimum RMS voltages as well as the maximum THD_V levels do not violate the allowable limits. Besides, it can be seen that the results obtained from the PPSOGSA are better than those obtained from the abovementioned algorithms.

5. CONCLUSIONS

In this paper, the application of a new hybrid PPSOGSA algorithm for solving the optimal placement and sizing of inverter-based distributed generation units and shunt capacitors in radial distribution systems with linear and non-linear loads is presented. The efficiency and the search performance of the algorithm are studied and evaluated on the standard IEEE 33- and 69-bus test systems with the objective of minimizing the total active power losses. Results obtained using the proposed approach are compared with those obtained using other optimization algorithms, such as the original PPSO and GSA, and those reported in the literature.

The main conclusions arising from the results and discussion are as follows:

- The results obtained using the proposed PPSOGSA algorithm are in accordance with the considered objective function, and all the specified constraints are met.

- By comparing the results obtained using the PPSOGSA algorithm with those obtained using the original PPSO and GSA optimization algorithms, for both the sinusoidal and non-sinusoidal operating conditions, it is found that the proposed PPSOGSA approach provides effective, robust, and high-quality solutions.
- It is found that the results obtained using the PPSOGSA algorithm for the sinusoidal operating condition are either better or comparable to those obtained by other techniques from the literature.
- It is found that the proposed PPSOGSA approach can converge to its global optimal solution after lower numbers of iterations compared to the original PPSO and GSA optimization algorithms.
- It is shown that the performance of the distribution system can be significantly improved in terms of reducing power losses and improving voltage profile and power quality with proper placement and sizing of inverter-based DG units and shunt capacitors.
- It is established that the solutions to the problem of the optimal placement and sizing of DGs and capacitors found for the sinusoidal operation condition, in the presence of harmonics, are not acceptable, because they lead to the high distortion levels.
- Regardless of the form of the objective function, the proposed PPSOGSA algorithm can be quickly and easily applied to any other distribution system with different types of non-linear loads and distributed generation units.

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