Optimally Placing Photovoltaic Systems in Distribution Networks Considering the Influence of Harmonics on Power Losses

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Abstract: Fossil fuels cause many negative impacts on the environment. Thus, the integration of renewable energy sources into traditional systems is increasingly prioritized for development. In this paper, Improved Coyote Optimization Algorithm (ICOA) is proposed for finding the most suitable location and the best capacity of photovoltaic distributed generators (PDGs) in radial distribution systems (RDSs). This new algorithm is an upgraded version of Coyote Optimization Algorithm (COA) and it has a better performance, a faster convergence speed and a more stable feature than its original form. The study focuses on the main objective function of minimizing both total active power losses on conductors and the impact of harmonics on node voltage and current flowing in distribution lines. In addition to currents with base frequency, harmonic flows also cause active power loss in distribution lines and the negative impact is also considered in the paper as a novelty. ICOA together with COA and Salp Swarm Algorithm (SSA) are applied for the IEEE 69-node radial distribution system for comparison with other methods in the literature. The comparative analysis sees that ICOA is a powerful method in optimally placing PDGs for reducing power loss and harmonic distortions.

Keywords: Coyote optimization algorithm; photovoltaic distributed generator; power losses; harmonic distortions; distribution lines.

Nomenclature

$CtrlV_v^{Min}, CtrlV_v^{Max}$	The lowest and highest values of the v^{th} control variable
$CtrlV_{v,co,pa}^{New}$	The new value of the v^{th} control variable in the co^{th} solution in pa^{th} pack
C, C^{Max}	The current and maximum values of pairs of close solutions
$\Delta V_{Bs,co,pa}$	The voltage, y at the Bs^{th} node corresponding to the co^{th} solution in the pa^{th} pack
$\Delta I_{Bh,co,pa}$	The current violation penalty for the Bh^{th} branch corresponding to the co^{th} solution in the pa^{th} pack
$\Delta THD_{Bs,co,pa}$	The total harmonic distortion violation penalty at the Bs^{th} node corresponding to the co^{th} solution in the pa^{th} pack
$\Delta IHD_{Bs,co,pa}^{h}$	The individual harmonic distortion violation penalty at the Bs^{th} node corresponding to the co^{th} solution in the pa^{th} pack
$FF_{co,pa}$	The current fitness value at the co^{th} solution in the pa^{th} pack
$FF_{co,pa}^{New}$	The new fitness value at the co^{th} solution in the pa^{th} pack
$FF_{b,pa}$	The fitness value of b^{th} solution in the pa^{th} pack
$FF_{a,pa}$	The fitness value of a^{th} solution in the pa^{th} pack
$FF_{mean,pa}$	The average fitness value of solutions in the pa^{th} pack
$FF_{Lbest,pa}$	The best fitness value in the pa^{th} pack
H	The maximum number of the order harmonic
$I_{Bh,PDG}$	The current magnitude at the Bh^{th} branch after connecting PDGs

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$I_{Bh}^{1}, I_{Bh,PDG}^{1}$	The current magnitude at the fundamental frequency before and after integrating PDGs
$I_{Bh}^{h}, I_{Bh,PDG}^{h}$	The current magnitude at the higher order frequency before and after integrating PDGs
$IHD_{V,Bs}^{h}$	The individual voltage harmonic distortion at the h^{th} order harmonic of the Bs^{th} node
I^{Max}	The maximum current magnitude limit
IHD^{Max}	The maximum limit of the individual harmonic distortion
$I_{Bh,co,pa}$	The current magnitude at the Bh^{th} branch corresponding to the co^{th} solution in the pa^{th} pack
$IHD_{Bs,co,pa}^{h}$	The individual harmonic distortion values at the Bs^{th} node corresponding to the co^{th} solution in the pa^{th} pack
It, It^{Max}	The current number of iteration and the maximum number of iteration
N_{Bh}	The total branch number
N_{PDG}	The total photovoltaic distributed generator number
N_{Ld}	The total load number
N_{co}	The coyote number in the community
N_{pa}	The coyote pack number in the community
N_{Bs}	The total bus number
N_{v}	The total control variable number
N_{po}	The number of coyote population
OF_{A}	The first component value in the multi-objective function
OF_{B1}	The first part value in the second component of the multi-objective function
OF_{B2}	The second part value in the second component of the multi-objective function
OF_{B}	The second component value in the multi-objective function
$OF_{co,pa}$	The objective function value at the co^{th} solution in the pa^{th} pack
$P_{Ls}, P_{Ls,PDG}$	The total active power loss before and after integrating PDGs
$P_{Ls,PDG,l}$	The active power loss at the Bh^{th} branch after integrating PDGs
P_{Gr}	The total active power from substation
$P_{Ld,l}$	The total active power of loads at the l^{th} load
$P_{PDG,p}$	The capacity of PDG at the p^{th} PDG
P_{w}	The control parameter in the extra algorithm
$P_{PDG}^{Min}, P_{PDG}^{Max}$	The minimum and maximum capacity of PDG
R_{Bh}	The resistance value at the Bh^{th} branch in the system
$rd, rd_{1}, rd_{2}, rd_{3}$	The numbers are generated in the range of [0, 1]
ρ	The penalty factor in the fitness objective function
$S_{co,pa}$	The current solution of the co^{th} solution in the pa^{th} pack
S^{Min}, S^{Max}	The minimum and maximum limits of solution
$S_{co,pa}^{New}$	The new solution of the co^{th} solution in the pa^{th} pack
$S_{Lbest,pa}$	The best solution in the pa^{th} pack
$S_{r1,pa}, S_{r2,pa}$	The solutions which are randomly taken in the pa^{th} pack
S_{Gbest}	The best solution in the population
$S_{Lbest,1}, S_{Lbest,2}, S_{Lbest,3}$	The best solutions which are randomly taken from different packs
$THD_{V,Bs}$	The total voltage harmonic distortion at the Bs^{th} node
THD^{Max}	The maximum limit of the total harmonic distortion

$THD_{V,Bs,PDG}$	The total voltage harmonic distortion at the Bu^{th} node after integrating PDGs
$THD_{Bs,co,pa}$	The total harmonic distortion values at the Bs^{th} node corresponding to the co^{th} solution in the pa^{th} pack
V_{Bs}^{h}	The voltage magnitude for the h^{th} order harmonic at the the Bs^{th} node
V_{Bs}^{1}	The voltage magnitude for the fundamental frequency at the Bs^{th} node
V^{Min}, V^{Max}	The minimum and maximum voltage magnitude limits
$V_{Bs,PDG}$	The total voltage magnitude at fundamental and higher order frequencies of the Bs^{th} node after integrating PDGs
$V_{Bs,PDG}^{1}$	The fundamental voltage magnitude at the Bs^{th} node after integrating PDGs
$V_{Bs,co,pa}$	The node voltage at the Bs^{th} node corresponding to the co^{th} solution in the pa^{th} pack

Abbreviations
ABC
Artificial Bee Colony
AGA
Adaptive Genetic Algorithm
ALOA
Ant Lion Optimization Algorithm.
BBO
Biogeography Based Optimization
BFOA
Bacterial Foraging Optimization Algorithm
COA
Coyote Optimization Algorithm
FPA
Flower Pollination Algorithm
GA
Genetic

Algorithm.
HAS
Harmony Search Algorithm
ICOA
Improved Coyote Optimization Algorithm
IWO
Invasive Weed Optimization Algorithm
PBIL
Population-based Incremental Learning Algorithm
PSO
Particle Swarm Optimization
QOTLBO
Quasi-Oppositional Teaching Learning Based Optimization
SA Simulated Annealing
SCA
Sine Cosine Algorithm
SSA
Salp Swarm Algorithm

WOA
Whale Optimization Algorithm

1. Introduction

In order to minimize the impact of fossil energy sources on the environment, renewable energy sources are increasingly developing in most countries around the world. The connection of renewable energy sources such as wind energy, solar energy, geothermal energy, ocean wave energy, etc. must be carefully considered. Many researchers have focused on analyzing the effects of this grid integrated generator system to maximize benefits [1-2]. The integration can bring many benefits to the distribution systems such as improving voltage of loads, mitigating harmonic distortions, reducing power loss on the transmission lines, minimizing emissions and reducing operating costs [3]. However, many studies have shown that improper connection of these distributed sources can cause undesirable effects and negatively impact on the economy, technology and environment [4]. Thus, researchers focused on determining the optimal installation of distributed generators (DGs) in the distribution systems. In Ref. [5], authors proposed ALOA for searching the optimal location and capacity of single and multiple renewable distributed generations. Their solution has succeeded in minimizing the power of loss and maximizing saving cost of energy loss in the radial distribution systems. Besides, the authors in Ref. [6] also reduced total power loss on the transmission lines by applying GA as an optimization tool with multiple placements of DGs. By determining the suitable installation of DGs, the total power loss is significantly reduced in a test case, IEEE 14-node network. For the same target of the loss reduction maximization, the study [7] used FPA to determine the appropriate capacity and suitable placement of photovoltaic - based distributed generation in distribution system with 41 nodes. The results showed the positivity of the solution in maximizing the benefits. In addition to reducing losses, many studies have tried to achieve the high voltage stability by adding DGs into distribution systems [8-11]. As shown in the numerical results, the reduction of the power loss and the improvement of voltage stability were highly effectively after connecting DGs by using AGA, SA, QOTLBO and ABC, respectively. Additionally, in Refs. [12-13], analytical method and HSA have also been used for determining the appropriate integration strategy of DGs in the aim of the loss reduction and voltage improvement for IEEE 33-node and 69-node systems. Those authors indicated the strong impact of the DGs installation on the economic and technical evaluations of a distribution system. With the desire to consider comprehensively the optimization problem of DGs, the authors in Refs. [14-15] proposed BFOA and IWO respectively for reducing of power loss as well as operating costs and improving voltage profile in the distribution system. The results have proven that the integration of DGs into grid not only improved the technical issues in the system but also helped to save costs during operation. With the same test systems and objective functions, the authors in Refs. [16-18] proposed strong hybrid methods such as WOA-SCA, PBIL-PSO and GA/PSO, respectively for solving the optimization problem of integrating DGs. The efficiency of these hybrid methods has been proven by comparing the obtained solutions. Furthermore, another research case in Ref. [19] has focused on the study for reliability enhancement by connecting of DGs. These authors have used an average index of the interruption frequency, the expected interruption cost and the interruption duration for analyzing reliability indices and losses. That paper demonstrated that the reliability of the system can be enhanced thanks to the selection of suitable installation of DGs.

In general, almost all previous studies only focused on improving voltage quality and minimizing power loss. They have not concerned another important element of harmonic flows. For distribution systems with nonlinear loads, the existence of harmonics is inevitable and it can negatively affect the electric device if values of the total harmonic distortion and the individual harmonic distortion exceed allowed limits. Thus, a high number of researchers has identified the danger of harmonics and suggested adding DGs in distribution systems to avoid the unintentional consequence [20-22]. Specifically, BBO [20] and sensitivity analysis [21] have been respectively applied for installing DGs to mitigate the average value of the total voltage harmonic distortion.

Nonlinear loads have been added in the distribution systems in charge of generating harmonic flows with different amplitudes and different orders. Power flows on distribution lines were still solved by using the forward/backward sweep technique (FW/BWST) similarly as the systems without nonlinear loads. Besides, other authors in Ref. [22] have considered for minimizing harmonics as an objective function under many constraints of node voltage, harmonics, sizing and penetration limits. Clearly, by using the optimization algorithm for searching the optimal position and capacity of multiple DGs, harmonics have been drastically reduced and obtained results have satisfied IEEE Std. 519 exactly. However, most of the studies that have harmonic analysis calculated only loss and voltage values at the fundamental frequency. Realistically, losses and voltages persist at the higher order frequency [23]. Therefore, it is important to study and compute numerical results at frequency orders to obtain exact solutions.

In this paper, Improved Coyote Optimization Algorithm (ICOA) [24] is applied as an optimal method for determining the suitable location and capacity of Photovoltaic Distributed Generators in IEEE 69-node radial distribution system. ICOA is an updated version of COA, so it has inherited the outstanding features of COA and the improvements to the original algorithm will greatly contribute to enhancing the performance and stability of the algorithm. The main goal is to minimize a bi-objective function including the power loss and the harmonic distortions under the multiple constraints. In the power loss computation process, the impact of all harmonics on the power loss of all conductors is considered unlikely previous studies that only considered the fundamental frequency current. In terms of harmonic objective, total harmonic distortion and individual harmonic distortion are calculated on average and the result become the second objective in the bi-objective function of the problem. On the other hands, basic constraints of distribution systems and additional advanced constraints regarding harmonics are also taken into account in the study. The increase of voltage amplitude due to the impact of harmonics is also calculated and added to voltage of loads at the fundamental frequency. In summary, the novelties of the paper are as follows:

1. Consider harmonics' influence on power loss of conductors. The power loss is also a part of bi-objective function and considered in the power balance constraint.
2. Consider harmonics' influence on load voltage. Voltage amplitude of loads, which is increased due to the influence of harmonics, is constrained within an allowable range of distribution systems.
3. Apply SSA, COA and ICOA for the problem with new proposals in objective function and constraints.

The main contributions of this study can be briefly summarized into three main points as follows:

1. Proposed a novel method with high efficiency (ICOA) in finding the optimal solution for the position and capacity of PDGs in the system to maximize benefits. The obtained results will be compared with implemented methods and published methods to prove the superiority of the proposed method.
2. Analyzed the effects of PDGs when integrated into the distribution system, IEEE 69-node system.
3. Considered reduction of losses and harmonics in the system with nonlinear loads. Besides, the values of loss and voltage are calculated in the frequency orders to obtain the correctly numerical results.

The remaining contents of the paper are organized as follows: Sec. 2 presents the objective function and the constraints of the considering problem, call is the problem formulation. Sec. 3 introduces the proposed method and describes the application of the method to find the optimal location and capacity of PDGs in the distribution system, name is the proposed method. Sec. 4 shows all results obtained from the simulation and makes the discussion, call is the simulation results and discussion. The last section is the summary for the whole contents of this paper, name is conclusions.

2. Problem Formulation

A. The Objective function

In this study, power losses and harmonic flows are important factors in evaluating the efficiency and power quality of the distribution system. Hence, they are considered as two main components in the multi-objective function of the problem. The two single objectives are expressed in detail as follows:

A.1. The first single objective-Total power loss

The power loss reduction is considered as a member of objective function due to the advantage of economic benefits. If power loss reduction is effectively finished, energy loss in kWh and energy loss cost in $ are also significantly optimized over scheduled horizon. Therefore, power losses on the transmission lines should be taken seriously and become an evaluation criterion of connecting PDGs in the distribution systems [25]. The calculation of the total power loss after and before connecting PDGs is shown in Eq. (1) and Eq. (2) [20, 23], respectively.

$$P_{Ls,PDG} = \sum_{Bh=1}^{N_{Bh}} \left(I_{Bh,PDG}\right)^2 . R_{Bh} = \sum_{Bh=1}^{N_{Bh}} \left(\sqrt{\left|I_{Bh,PDG}^{1}\right|^2 + \sum_{h=2}^{H} \left|I_{Bh,PDG}^{h}\right|^2} \right)^2 . R_{Bh} \tag{1}$$

$$P_{Ls} = \sum_{Bh=1}^{N_{Bh}} (I_{Bh})^2 . R_{Bh} = \sum_{Bh=1}^{N_{Bh}} \left(\sqrt{|I_{Bh}^{1}|^2 + \sum_{h=2}^{H} \left|I_{Bh}^{h}\right|^2} \right)^2 . R_{Bh} \tag{2}$$

To evaluate the fitness function simply, the components in general as well as the first component in the multi-objective function will be kept within the range of 0 to 1. Clearly, the first component associated with the power loss is always expected to be minimum and it is mathematically formed as follows:

$$Minimize\ OF_A = \frac{P_{Ls,PDG}}{P_{Ls}} \tag{3}$$

A.2. The second single objective-Harmonic distortions

Harmonic flows make the change of voltage wave form and also increase the voltage magnitude. These harmonic flows have different orders and different magnitudes that considerably influence voltage of loads. Each harmonic order has individual impact on the voltage of loads and all harmonic orders cause a stronger impact on the voltage. So, the individual impact of each harmonic order and the general impact of all harmonic orders must be considered in the load voltage quality evaluation. As a result, the total voltage harmonic distortion ($THD_{V,Bs}$) caused by all harmonic orders and the individual voltage harmonic distortion at the higher order frequency ($IHD_{V,Bs}^{h}$) are considered as the second component of the multi-objective function. $THD_{V,Bs}$ and $IHD_{V,Bs}^{h}$ are obtained by using the two following formulas [26].

$$THD_{V,Bs}(\%) = \frac{\sqrt{\sum_{h=2}^{H} \left|V_{Bs}^{h}\right|^2}}{\left|V_{Bs}^{1}\right|} . 100 \tag{4}$$

$$IHD_{V,Bs}^{h}(\%) = \frac{\left|V_{Bs}^{h}\right|}{\left|V_{Bs}^{1}\right|} . 100 \tag{5}$$

The second component consists of two parts, $THD_{V,Bs}$ and $IHD_{V,Bs}^{h}$. In this study, those parts are considered for minimizing the impact of harmonics on the voltage of the distribution systems. Thus, we propose Eq. (6) and Eq. (7) to calculate representative values and to keep the second single objective within the range of 0 and 1.

$$OF_{B1} = 1 - \frac{1}{e^{\max(THD_{V,Bs})}} \tag{6}$$

$$OF_{B2} = 1 - \frac{1}{e^{\max(IHD_{V,Bs}^{h})}} \tag{7}$$

Because the two parts have the same range within 0 and 1 and they have the same impact on the voltage quality, their mean is considered as the second singe objective in the bi-objective function of the problem. As a result, the second objective in formula (8) is written to calculate the equilibrium value for this second component.

$$Minimize\ OF_B = \frac{OF_{B1}+OF_{B2}}{2} \tag{8}$$

In this research, the multi-objective function is used to evaluate the quality of the solution and it is established as Eq. (9)

$$Minimize\ OF = min[(w_A.OF_A) + (w_B.OF_B)] \tag{9}$$

Finally, in this case, the weight sum method is applied to make decision for the value of the multi-objective function. The weight factor w_A associated with the first objective-power loss and the weight factor w_B associated with the second objective-harmonic distortions are constrained as follows [27].

$$0 \le w_A, w_A \le 1\ \&\ w_A + w_B = 1 \tag{10}$$

B. Constraints

B.1. The power balance constraint

In this case, the distribution system is integrated PDGs for maximum benefits. Thus, the power balance equation in this system can be presented as [18]

$$P_{Gr} = \sum_{l=1}^{N_{Ld}} P_{Ld,l} + \sum_{Bh=1}^{N_{Bh}} P_{LS,PDG,Bh} - \sum_{p=1}^{N_{PDG}} P_{PDG,p} \tag{11}$$

B.2. The branch current constraint

In order to keep the thermal component on the transmission line from being altered with the integration of the PDGs. The current magnitude at harmonic orders after connecting PDGs should not exceed the limit as [28]

$$I_{Bh,PDG} \le I^{Max}, Bh = 1, 2, \dots, N_{Bh} \tag{12}$$

B.3. The harmonic voltage distortion constraints

The harmonic distortions in the distribution system can damage the electronic equipment that connected on the transmission lines. Therefore, the harmonic values at nodes should comply with the IEEE Std. 519 about allowed limits.

The limit for the total voltage harmonic distortion [29]

$$THD_{V,Bs}(\%) \le THD^{Max}(\%) \tag{13}$$

The limit for the individual voltage harmonic distortion [30]

$$IHD_{V,Bs}^{h}(\%) \le IHD^{Max}(\%) \tag{14}$$

B.4. The bus voltage limits

The integration of PDGs can have a powerful effect on the distribution system, such as voltage profile, stability, reliability, protection, etc. Therefore, it is necessary to keep the total voltage magnitude at the harmonic orders PDGs within the allowable limits as below [28, 23]:

$$V^{Min} \le |V_{Bs,PDG}| \le V^{Max}, Bu = 1, 2, \dots, N_{Bs} \tag{15}$$

$$V_{Bs,PDG} = V_{Bs,PDG}^{1} \cdot \sqrt{1 + \left(\frac{THD_{V,Bs,PDG}}{100}\right)} \tag{16}$$

B.5. The PDG's penetration limits

In this paper, the penetration of each PDG is considered with variation within a predetermined limits and the total capacity should not exceed the total load demand in the distribution system. So, the penetration level is kept in the constraints as below [20, 31]:

$$\sum_{p=1}^{N_{PDG}} P_{PDG,p} \le \sum_{l=1}^{N_{Ld}} P_{Ld,l} \tag{17}$$

$$P_{PDG}^{Min} \le P_{PDG,p} \le P_{PDG}^{Max} \tag{18}$$

3. The Proposed Method

In this study, two enhancements in the Coyote Optimization Algorithm are implemented to solve the problem of optimization and called ICOA. ICOA is developed to improve the COA's efficiency as well as the speed of convergence [32]. In both COA and ICOA, the two main components that are represented for individual in the coyote community are the quality of social condition and the social condition. A social condition represents as an optimal solution, while the quality of the social condition corresponds to the fitness of the solution. In the applied algorithms, the number of coyote individuals in each group (N_{co}) and the number of coyote groups in the coyote community (N_{pa}) are the two main determinants of population (N_{po}). Hence, the total population is the multiplication of N_{pa} and N_{co}.

As mentioned, the grid integrated PDGs system brings many economic and technical benefits. However, this integration can cause undesirable effects on the system. Hence, the calculation of power flow and harmonic flow when connecting PDGs should be calculated carefully. In this study, the flow analysis at the fundamental frequency and at the high order frequency is based on forward / backward sweep technique (FW / BWST) which is clearly described in [33] and the nonlinear loads in the system are also considered as injectors of harmonic currents. In FW / BWST, the relationship between the branch currents and the injected bus currents are built by backward sweep. Besides, the forward sweep is responsible for determining the bus voltages by using the aforementioned relationship in the distribution system. The process of using ICOA for finding the optimal solution of PDGs installation can be briefly summarized as below:

STEP 1: Determine the initial parameters such as N_{co}, N_{pa}, and It^{Max}

STEP 2: Randomly produce the initial solution set in the predetermined limits of [S^{Min}, S^{Max}] by using Eq. (19):

$$S_{co,pa} = S^{Min} + rd.(S^{Max} - S^{Min});\ \ co = 1,2,\dots,N_{co}\ \&\ pa = 1,2,\dots,N_{pa} \tag{19}$$

STEP 3: Solve the power flow and harmonic flow by using the BW/FW sweep method [33]. Calculate the penalty level for the node voltages, the branch currents and the harmonics of solutions by applying Eq. (20) – Eq. (23), respectively:

$$\Delta V_{Bs,co,pa} = \begin{cases} |V^{Max} - V_{Bs,co,pa}|, if\ V_{Bs,co,pa} > V^{Max} \\ |V^{Min} - V_{Bs,co,pa}|, if\ V_{Bs,co,pa} < V^{Min} \\ 0\ else \end{cases} \tag{20}$$

$$\Delta I_{Bh,co,pa} = \begin{cases} |I^{Max} - I_{Bh,co,pa}|, if\ I_{Bh,co,pa} > I^{Max} \\ |I^{Min} - I_{Bh,co,pa}|, if\ I_{Bh,co,pa} < I^{Min} \\ 0\ else \end{cases} \tag{21}$$

$$\Delta THD_{Bs,co,pa} = \begin{cases} |THD^{Max} - THD_{Bs,co,pa}|, if\ THD_{Bs,co,pa} > THD^{Max} \\ 0\ else \end{cases} \tag{22}$$

$$\Delta IHD^{h}_{Bs,co,pa} = \begin{cases} |IHD^{Max} - IHD^{h}_{Bs,co,pa}|, if\ IHD^{h}_{Bs,co,pa} > IHD^{Max},\ h > 1 \\ 0\ else \end{cases} \tag{23}$$

Calculate the fitness value of solutions by using Eq. (24) and start the first computation iteration (i.e. set $It = 1$)

$$FF_{co,pa} = OF_{co,pa} + \rho.\left(\sum_{Bs=1}^{N_{Bs}} \Delta V_{Bs,co,pa} + \sum_{Bh=1}^{N_{Bh}} \Delta I_{Bh,co,pa} + \sum_{Bs=1}^{N_{Bs}} \Delta THD_{Bs,co,pa} + \sum_{Bs=1}^{N_{Bs}} \Delta IHD^{h}_{Bs,co,pa}\right) \tag{24}$$

STEP 4: Determine and save the local best solution ($S_{Lbest,pa}$) in each pack and the global best solution (S_{Gbest}) in the current population. Produce new solutions by applying Eq. (25) below:

$$S^{New}_{co,pa} = S_{co,pa} + rd_1.\left(S_{Lbest,pa} - S_{r1,pa}\right) + rd_2.\left(S_{Gbest} - S_{r2,pa}\right);\ co = 1,2,\dots,N_{co}\ \&\ pa = 1,2,\dots,N_{pa} \tag{25}$$

STEP 5: In each generated new solution, the control variables of the new solutions are adjusted according to the predefined rules as Eq. (26)

$$CtrlV_{v,co,pa}^{New} = \begin{cases} CtrlV_{v}^{Min}, if\ CtrlV_{v}^{Min} > CtrlV_{v,co,pa}^{New} \\ CtrlV_{v}^{Max}, if\ CtrlV_{v}^{Max} < CtrlV_{v,co,pa}^{New} \\ CtrlV_{v,co,pa}^{New}\ else. \end{cases}$$
$$v = 1, 2, \ldots, N_v;\ co = 1, 2, \ldots, N_{co};\ pa = 1, 2, \ldots, N_{pa} \tag{26}$$

STEP 6: Apply penalty functions at STEP 3 to compute the fitness value of the objective function for evaluating the quality of each solution by using Eq. (24).

STEP 7: Retain the solutions which have good quality by using Eq. (27) – Eq. (28)

$$\mathrm{S}_{co,pa} = \begin{cases} S_{co,pa}^{New}, if\ FF_{co,pa} > FF_{co,pa}^{New} \\ \mathrm{S}_{co,pa} \quad else \end{cases} \tag{27}$$

$$\mathrm{FF}_{co,pa} = \begin{cases} FF_{co,pa}^{New}, if\ FF_{co,pa} > FF_{co,pa}^{New} \\ \mathrm{FF}_{co,pa} \quad else \end{cases} \tag{28}$$

STEP 8: In this task, the second improvement is comprised of two update equations for generating a new solution. The selection of the update equation depends on the survey result of the control parameter (P_w) within the range of [0, 1] to choose the suitable parameter and the calculation result of the proportional value (R) of the two counters (C and C^{Max}). As mentioned, it is important to determine the value of the counter C. Its value is changed when the difference of two adjacent fitness values is less than the difference of the mean and best values in the pack. Specifically, for each pack in the population, a new solution can be produced by using Eq. (29) or Eq. (30).

$$S_{pa}^{New} = S_{Gbest} + rd_1.(S_{Gbest} - S_{Lbest,1}) + rd_2.(S_{Gbest} - S_{Lbest,2}) \tag{29}$$

$$S_{pa}^{New} = S_{Gbest} + rd_1.(S_{Gbest} - S_{Lbest,1}) + rd_2.(S_{Gbest} - S_{Lbest,2}) + rd_3.(S_{Gbest} - S_{Lbest,3}) \tag{30}$$

Besides, the C^{Max} value is also calculated based on the number of coyotes such as Eq. (31)

$$C^{Max} = \frac{N_{co} \times (1 + N_{co})}{2} \tag{31}$$

The calculation process to determine the condition for applying the update equation can be followed by the extra algorithm which is proposed in Ref. [24] as below box:

C=0;

For *a*=1 to (N_{co} – *1*)

For *b*=*a* + 1 to N_{co}

If $|FF_{b,pa} - FF_{a,pa}| < |FF_{mean,pa} - FF_{Lbest,pa}|$

C=C+1 (32)

End

End

End

Compute proportional value R as:

$$R = \frac{C}{C^{Max}} \tag{33}$$

If $R > P_w$

Apply Eq. (29) to produce the new solution

Else

Apply Eq. (30) to produce the new solution

End;

After a new solution has been generated, each control variable in that solution is adjusted.
Run the power flow and harmonic flow.
Calculate the fitness value of the objective function after applying penalty terms.
STEP 9: Determine the best solution in population.
STEP 10: Check the condition in Eq. (34). If it is satisfied, exchange the solutions between the two randomly selected packs. Otherwise, check the criteria to exit the iteration as Eq. (35)

$$rd < \frac{0.01}{2}.N_{co}^2 \tag{34}$$

$$It = It^{Max} \tag{35}$$

If the stopping criterion is not satisfied, come back to STEP 4 and the number of iterations is increased by one.

4. The Simulation Results

In this paper, ICOA is proposed for finding the location and capacity of three PDGs in the IEEE 69-node radial distribution system. This system has 69 nodes with the total load capacity of 3.8019 MW and 2.6941 MVar. The structure of the system is shown in Figureure 1.

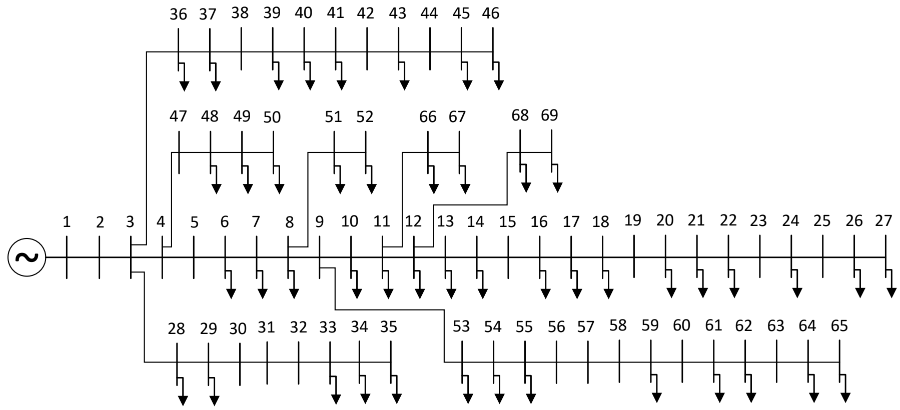

Figure 1. IEEE 69-node radial distribution system

As mentioned, this test system will be considered in the presence of harmonics. The harmonic flows whose magnitude, angle and harmonic order are shown in Figureure 2 are injected to load locations such as 10, 12, 18, 19, 22, 25, 31, 38, 46, 56, and 65. According to the IEEE Std. 519, the maximum allowable limits of the total voltage harmonic distortion and the individual voltage harmonic distortion are 5% and 3%, respectively. Besides, the voltage magnitude at each node should also be within the best range of [0.95, 1.05] (pu) [34].

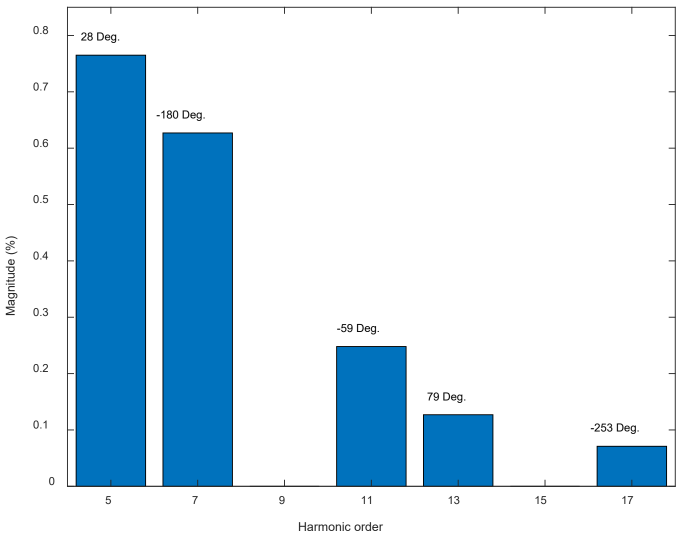

Figure 2. The detailed information of five harmonic flows

In the sum of weight method, the first factor w_A is associated with the power loss reduction and the second factor w_B is concerned with the harmonic mitigation. In this study, the minimization of both the power loss and harmonics is the main goal. However, the power loss reduction is assessed to be more important than harmonic reduction. Therefore, the first factor will have the value greater than the second factor. Specifically, w_A = 0.8 and w_B = 0.2. All simulations are implemented on personal computer by using MATLAB software. For personal computer specifications, Processor: 1.8 GHz and RAM: 8.0 GB. For the three implemented methods of SSA, COA and ICOA, the search region for the optimal location of each PDG will vary within the node limit of [2, 69] and the search capacity limit will also change in range of [0.0, 2.0] (MW). It^{Max} is surveyed and selected is 100 with 60 trial runs (Tr^{Max}) for each method. For running both COA and ICOA, N_{co} and N_{pa} are surveyed for determining the most suitable value. In this particular case, the selected values of N_{co} and N_{pa} should fall within the range of three numbers as 3, 4 and 5. The value pairs of N_{co} and N_{pa} are combined together and finally, the chosen result is 4 for N_{co} and N_{pa}. Besides, in ICOA, P_w in the extra algorithm is taken as 0.2 [24]. Additionally, for SSA implementation, N_{po} is set to 20 for a fair comparison with three acceleration factors (c_1, c_2 and c_3). While c_1 is the value of the function of $2e^{-(4.It/It^{Max})^2}$, both c_2 and c_3 values are chosen randomly within the range of [0, 1] [35].

Due to the characteristics of the meta-heuristic algorithms, 60 trial runs are performed for three implemented methods with randomly generated initial population. The obtained results are re-sorted in the increasing order of fitness function t and presented as shown in Figure 3.

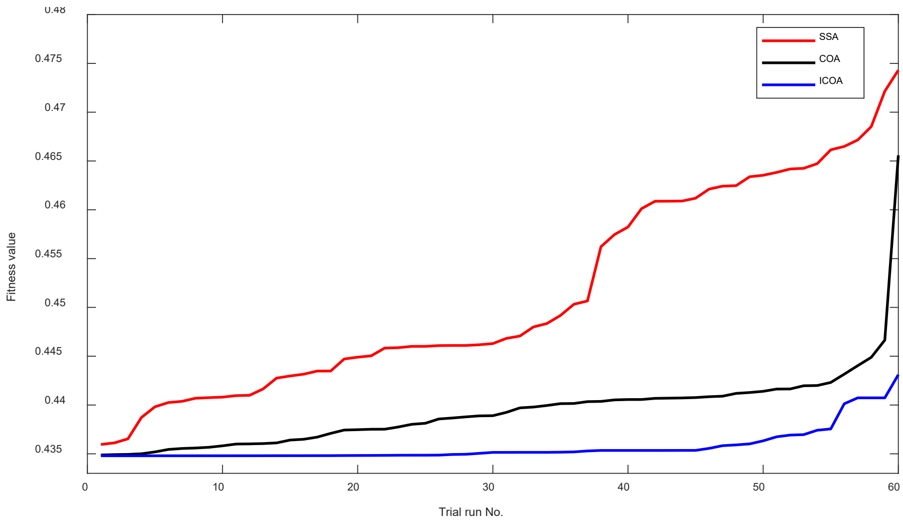

Figure 3. The re-sorted fitness values in order from smallest to biggest in 60 trial runs

By using the calculated results from Eq. (24), the worst fitness and the best fitness values are determined and the average fitness values of applied methods are computed in the 60 trials due to the stochastic characteristic of the heuristic algorithms. As shown in Table 1, the best fitness and the average fitness values of ICOA, COA and SSA are 0.4348 and 0.4358, 0.4350 and 0.4391, 0.4360 and 0.4513, respectively. Obviously, the best fitness value of ICOA is the lowest as compared to others. This shows that the optimal solution from ICOA has the highest quality. Additionally, the average fitness value of ICOA is also lower than COA and SSA. This value represents the stability of each method and the closer it is to the best fitness value, the more stable the method is. In other words, ICOA is more stable than others. Besides, the worst fitness value of ICOA in 60 trials is 0.4431 and it is the lowest value as compared to COA and SSA, 0.4467 and 0.4743, respectively. All the collected results have contributed to prove the high efficiency and stability of the proposed method. In addition, the number of fitness function evaluation is also calculated as the multiplication of the number of iterations and the population size in each trial run. This value of ICOA is smaller than SSA and equal to COA. In other words, ICOA uses fewer solutions to find the optimal solution. This saves data memory. All the above arguments have indicated that ICOA has a better stability and a stronger search feature than others in solving the same optimization problem.

Table 1. The best, the mean and the worst fitness values of the implemented methods in 60 trial runs

Method	The worst fitness value	The average fitness value	The best fitness value	The number of solution evaluations
SSA	0.4743	0.4513	0.4360	2000
COA	0.4467	0.4391	0.4350	1600
ICOA	0.4431	0.4358	0.4348	1600

Table 2. The first, the second and the total objective function values of the implemented methods at the best solution

Method	OF_A	OF_B	OF
SSA	0.3193	0.9027	0.4360
COA	0.3129	0.9235	0.4350
ICOA	0.3126	0.9235	0.4348

Table 3. The comparison of loss reduction of the implemented methods and the published methods at the best solution

Method	The optimal solution of three PDGs (Place – Capacity)	Power loss (MW)	Populatio n size	Iteration number
GA/PSO [18]	Node 21 – 0.9105 MW; Node 61 – 1.1926 MW; Node 63 – 0.8849 MW	0.0811	50	30
SA [9]	Node 18 – 0.4204 MW; Node 60 – 1.3311 MW; Node 65 – 0.4298 MW	0.0771	30	50
BFOA [14]	Node 27 – 0.2954 MW; Node 61 – 1.3451 MW; Node 65 – 0.4476 MW	0.0752	100	50
HSA [13]	Node 63 – 1.3024 MW; Node 64 – 0.3690 MW; Node 65 – 0.1018 MW	0.0868	30	60
IWO [15]	Node 27 – 0.2381 MW; Node 61 – 1.3266 MW; Node 65 – 0.4334 MW	0.0746	100	50
QOTLBO [10]	Node 15 – 0.8114 MW; Node 61 – 1.1470 MW; Node 63 – 1.0020 MW	0.0806	50	100
AGA [8]	Node 12 – 0.2720 MW; Node 21 – 0.3100 MW; Node 61 – 1.8610 MW	0.0707	80	300
SSA	Node 17 – 0.4118 MW; Node 61 – 1.5519 MW; Node 64 – 0.2886 MW	0.0719	20	100
COA	Node 11 – 0.5056 MW; Node 17 – 0.3791 MW; Node 61 – 1.6904 MW	0.0705	16	100
ICOA	Node 11 – 0.4883 MW; Node 17 – 0.3863 MW; Node 61 – 1.7331 MW	0.0704	16	100

Table 2 and Table 3 show the results of the best solution in 60 trials of implemented methods. The first component value in the multi-objective function of ICOA is 0.3126, corresponding to 0.0704 MW. Meanwhile, the values for COA and SSA are 0.3129 and 0.3193, corresponding to 0.0705 MW and 0.0719 MW, respectively. In addition, the proposed method is also compared with previously published methods of the power loss reduction in the grid integrated distributed generators system. As shown in Table 3, the power loss with DGs of GA/PSO, SA, BFOA, HSA, IWO, QOTLBO, AGA and ICOA is 0.0811 MW, 0.0771 MW, 0.0752 MW, 0.0868 MW, 0.0746 MW, 0.0806 MW, 0.0707 MW and 0.0704 MW, respectively. Explicitly, the power loss of ICOA is the smallest as compared with others. Individually, by installing the optimal location and sizing of PDGs that is proposed from the proposed method, the total power loss can be significantly reduced from 0.2253 MW to 0.0704 MW. Thereby, the determination of the suitable installation of PDGs has a great influence on the reduction of power loss in the distribution system. Besides, from the results that have been collected for the population and iteration numbers of the methods in Table 3, it has been shown that the population size that is used in the proposed method is significantly lower than the other methods. This indicates that the proposed method only requires a small population size to find a good quality solution. In terms of the iteration number, this number is equal to or higher than the compared methods. As mentioned, this number depends on the results of the survey and it should be large enough to ensure that the convergence is fully completed.

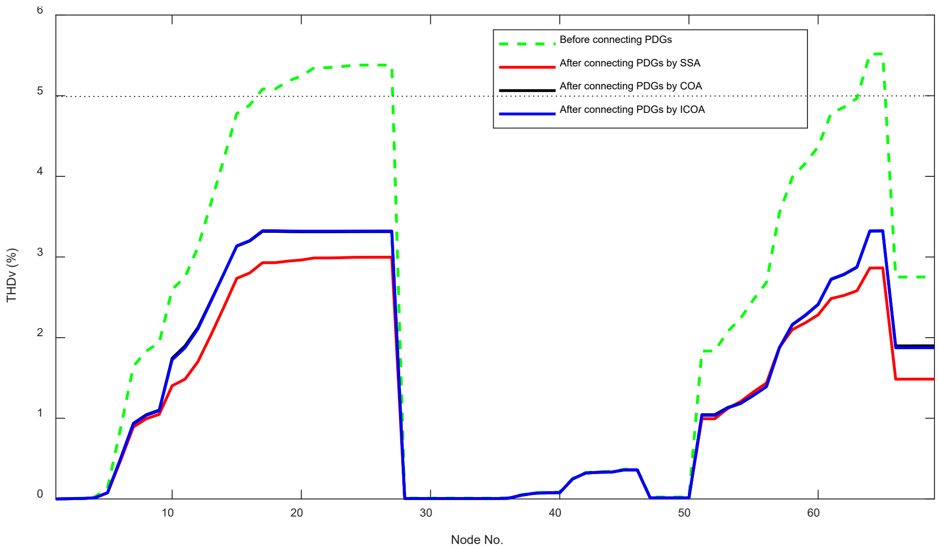

Figure 4. The THDv at each node before and after connecting PDGs

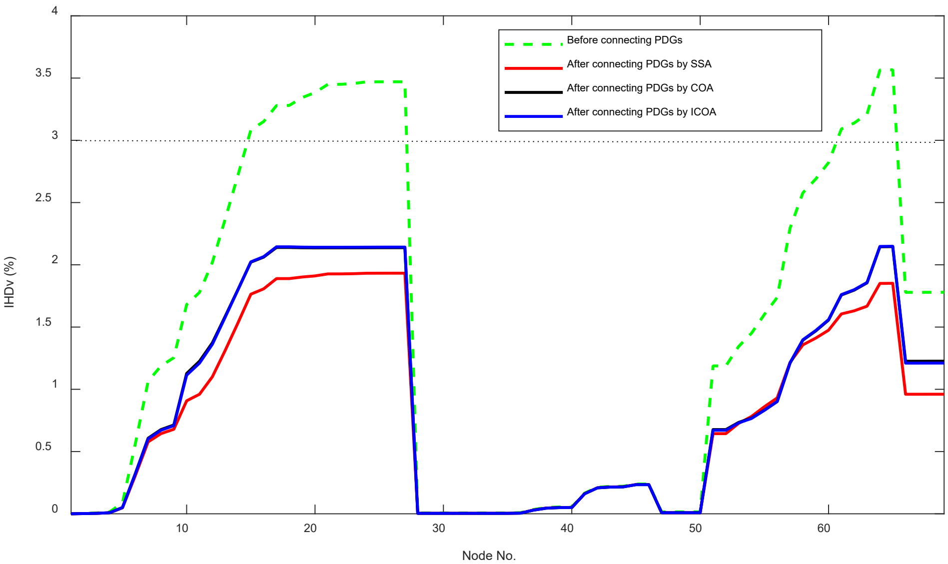

Figure 5. The IHDv at each node before and after connecting PDGs

For the second component value in the multi-objective function, this value of ICOA is 0.9235 and it is the same COA and bigger than SSA, 0.9235 and 0.9027, respectively. However, the multi-objective function is considered in this study. Therefore, the total objective function value is the decisive value for evaluating the effectiveness of the solution. The total objective function values of SSA, COA and ICOA are 0.4360, 0.4350 and 0.4348 respectively. As far as the obtained numerical results, the total objective value of the ICOA is the smallest. In other words, ICOA has a better performance of finding the optimal solution than the two implemented methods.

More details, Figures 4 and 5 show the harmonic distortion profiles in the IEEE 69-node distribution system. As mentioned, five harmonic flows are injected into the system, so the individual voltage harmonic distortion in at each node will have five values, corresponding to five harmonic orders. Therefore, here, the maximum value of individual voltage harmonic distortion at each harmonic order is denoted by IHD_V. As shown in the Figures, before the connection of PDGs, the maximum values of THD_V and IHD_V are equal to 5.5179% and 3.5665%, respectively. These values exceed the IEEE Std. 519 about the permissible limits of harmonics. However, after the connection of three PDGs, all THD_V and IHD_V values at the nodes decreased to the allowable limits as shown in Figures 4 and 5. Typically, the maximum value of THD_V and IHD_V which obtained from applying the optimal solution of ICOA is 3.3260% and 2.1488%, respectively. Obviously, thanks to the proper installation of PDGs, the harmonics of the system are drastically reduced. This shows the influence of integrating PDGs on harmonics. Therefore, the installation of PDGs should be carefully considered to mitigate the harmonics accordingly.

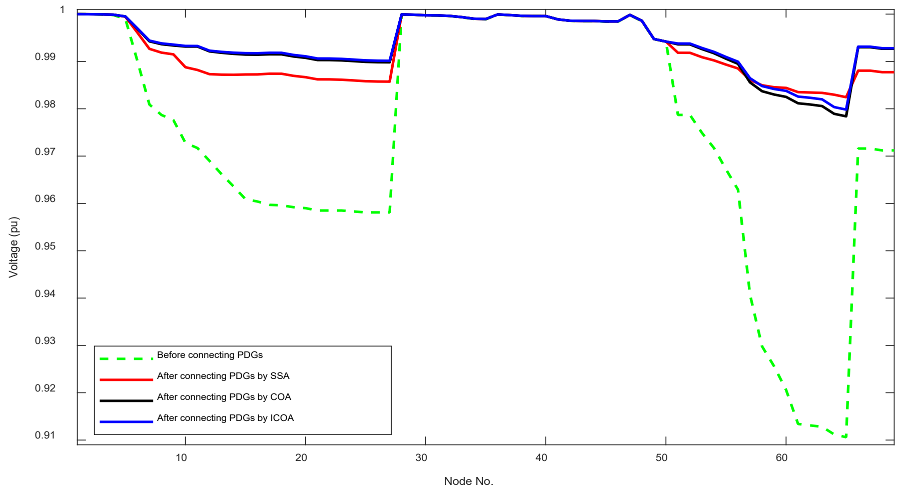

Figure 6. The voltage profile before and after connecting PDGs

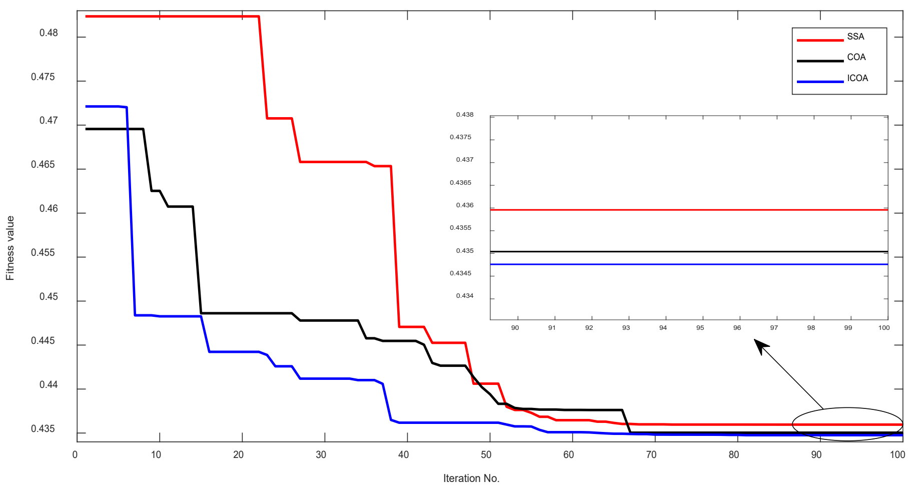

Figure 7. The convergence curves of implemented methods in 100 iterations

The voltage profiles of the implemented methods before and after integrating the PDGs are shown in Figure 6. Before connection, the minimum node voltage is 0.9106 pu. However, when there are properly integrated three PDGs into the system, the voltage profile improved significantly with the smallest node voltage of ICOA of 0.9798 pu. Thereby, it shows that the voltage quality has been enhanced thanks to the optimal installation of PDGs into the distribution system.

Figure 7 presents the convergence of these implemented methods. Like the plotted curves, ICOA found a better feasible solution than the others very early, at the 8^{th} iteration. Besides, ICOA also found the best quality solution at the earlier iteration than others, specifically, at the 63^{rd} iteration for ICOA, while at the 70^{th} iteration and at the 68^{th} iteration for COA and SSA, respectively. It indicates that ICOA has better convergence characteristics than compared methods. In short, thanks to suitable improvements in two update equations in COA that ICOA becomes an effective method with the high stability and the fast convergence speed. It is a superior optimization tool in solving the problem of optimizing the location and capacity of PDGs in the distribution system in particular and the optimization problems in general.

4. Conclusion

In this research, the improved coyote optimization algorithm is applied to optimize the position and capacity of PDGs in the IEEE 69-node radial distribution system. The main objective function of this work is to minimize power loss and harmonics in the system under the limit constraints of node voltage, branch current and harmonic distortions. Besides, the values of node voltage and power loss are also calculated at the frequency orders to obtain correctly numerical results. The optimal result found by the proposed method reduces power loss significantly from 0.2253 MW to 0.0704 MW, corresponding to 68.75% in the power loss reduction. In addition, THD_V and IHD_V also decreased positively from 5.5179% and 3.5665% to 3.3260% and 2.1488%, respectively. This is a clear demonstration of the benefits of properly integrating PDGs in reducing losses as well as harmonics. The found solution from ICOA is also compared to two implemented methods of SSA and COA as well as seven previously published methods of GA/PSO, SA, BFOA, HSA, IWO, QOTLBO and AGA. The obtained results showed that the proposed method is really an efficient, stable and fast convergence method in solving the optimization problem.

Data availability

The used data of the IEEE 69-node radial distribution system and the detailed information of harmonic flows are taken from Ref. [20] and Ref. [36], respectively.

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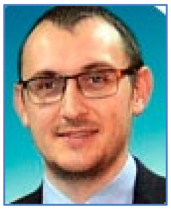

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