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Optimal Distributed Photovoltaic Units Placement in Radial Distribution System Considering Harmonic Distortion Limitation

Van-Duc Phan[1], Minh Quan Duong[2], Man Minh Doan[3] and Thang Trung Nguyen[4]*

[1]Faculty of Automobile Technology, Van Lang University, Ho Chi Minh City 700000, Vietnam.
[2]The University of DaNang-University of Science and Technology, Faculty of Electrical Engineering, DaNang city 550000, Vietnam.
[3]Faculty of Automation Technology, Thu Duc College of Technology, Ho Chi Minh City 700000, Vietnam.
[4]Power System Optimization Research Group, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City 700000, Vietnam
*Corresponding author: nguyentrungthang@tdtu.edu.vn
duc.pv@vlu.edu.vn, dmquan@dut.udn.vn, doanman2601@gmail.com

Abstract: Fossil fuels are used in the system to cause environmental pollution and global warming. Thus, nowadays, the use of renewable energy sources is becoming very popular in countries around the world. In addition to being environmentally friendly, installing of renewable energy sources has shown significant impacts on the power quality as well as on the operating costs of the system. In this paper, an effective, nature-inspired meta-heuristic approach is applied to research the optimal siting and sizing of distributed photovoltaic units (PVUs) in radial distribution systems. The main objective of this research is to focus on minimizing the power loss of the system while harmonic distortions are kept in the permissible limits of the IEEE Std. 519 and voltage profile is kept within the best range of voltage. The approach is called the Coyote Optimization Algorithm (COA), which is developed based on the behavioral characteristics of the coyote community, is introduced to ensure maximum benefits from the grid integrated PVUs system. This is a simple algorithm in application with few control parameters and it has the ability to expand the search zones and avoid local traps, resulting in a high performance and stability. The effectiveness of the method is demonstrated in comparison to other methods as Particle Swarm Optimization (PSO) and Salp Swarm Algorithm (SSA) in the IEEE 85-bus radial distribution system. The obtained results indicate the outstanding efficiency of the proposed method in maximizing the economic and technical benefits by optimal installation of distributed PVUs.

Keywords: Coyote optimization algorithm; distributed photovoltaic units; power loss; voltage profile; harmonics.

Nomenclature

$CV_{v,rd}$	The v^{th} control variable that is selected randomly from the predetermined limits
$CV_{v,r1,g}$, $CV_{v,r2,g}$	The control variables are taken at random from the first solution and the second solution in the g^{th} group
$Fit_{c,g}$, $Fit_{c,g}^{new}$	The current and new fitness values for the c^{th} solution at the g^{th} group
H	The maximum order harmonic number
I_b	The branch current before connecting PVUs
$I_{b,c,g}$	The current magnitude at the b^{th} branch corresponding to the c^{th} solution in the g^{th} group
I_{bPVU}	The branch current after connecting PVUs
I^{max}	The maximum current
$Iter^{max}$, $Iter$	The maximum and current iteration number
N_{bra}	The number of branches
N_{bu}	The number of buses

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N_g	The number of groups in coyote community
N_{loa}	The number of loads
N_{pvu}	The number of distributed photovoltaic units
N_{po}	The population number
N_v	The number of control variables
N_c	The number of coyotes
$ObF_{c,g}$	The current objective function value of the c^{th} solution at the g^{th} group
P_1, P_2	The scatter and association probabilities
P_{gri}	The active power from substation
$P_{los,b}$	The active power of the b^{th} branch
P_{loa}	The active load demand of the system
$P_{loa,l}$	The active power of loads at the l^{th} load
$P_{PVU}^{\min}$, $P_{PVU}^{\max}$	The minimum and maximum capacity of distributed photovoltaic units
$P_{pvu,p}$	The distributed photovoltaic unit's capacity at the p^{th} distributed photovoltaic unit
r_1, r_2, r_3	The random numbers from 0 to 1
R_b	The branch resistance
$So_{c,g}$	The current solution of the c^{th} coyote in the g^{th} group
$So^{\min}$, $So^{\max}$	The lower and upper bound of control variable
$So_{rd1,g}$, $S_{rd2,g}$	The randomly taken solution in the g^{th} group
SV_c^{min}, SV_c^{max}	The minimum and maximum predefined limits of the c^{th} control variable
$V_{bu,c,g}$, $IHP_{bu,c,g}$, $THP_{bu,c,g}$	Voltage, individual and total harmonic distortion at the bu^{th} bus corresponding to the c^{th} solution in the g^{th} group
V_{bu}	The voltage at the bu^{th} bus
$V^{\min}$, $V^{\max}$	The minimum and maximum limits of the voltage
λ_{IP}, λ_{VP}, λ_{HP}	The factors of current, voltage and harmonic penalties in the function

Abbreviations

ACO	The ant colony optimization
ALOA	The ant lion optimization algorithm
BBO	The biogeography-based optimization
CABC	The chaotic artificial bee colony
COA	The coyote optimization algorithm
DA	The dragonfly algorithm
MASCSA	Modified adaptive selection cuckoo search algorithm
MOGA	Multi-objective genetic algorithm
GA	The genetic algorithm
GSA	The gravitational search algorithm
PSO	The particle swarm optimization
SQPT	The sequential quadratic programming technique
SSA	The Salp swarm algorithm
WCA	Water cycle algorithm
PVUs	Distributed photovoltaic units

1. Introduction

Nowadays, it is very common to integrate distributed solar energy sources into distribution systems due to the great many benefits. By installing the distributed PVUs appropriately on the grid, the system can minimize power loss, enhance voltage quality, reduce operation and maintenance costs, etc. However, if distributed PVUs is not integrated properly, it will cause many undesirable effects such as voltage fluctuation, voltage flick, harmonic distortions, power loss, cost increases, etc. [1]. Therefore, the planning strategy for optimizing the installation of PVUs should be seriously considered.

As previous studies have demonstrated [2], the economic and technical benefits mainly affected on the location and capacity of distributed generation units (DGUs) that are integrated into the distribution system. The authors in [2-3] used GA for the optimal installations of DGUs in systems. The main objective function of these studies is to focus on minimizing power loss while still satisfying the current and voltage constraints. Besides, other researchers [4-5] have proposed PSO for solving the above optimization problem in order to improve voltage as well as minimize losses. The obtained results demonstrated that the proper determination of the position and capacity of the DGUs will maximize benefits. Moreover, for enhancing voltage stability, the authors in [6-7] have proposed DA and CABC as efficient optimization tools to solve this problem. Their proposed methods have been compared with other methods in popular systems such as 15-bus, 33-bus, 38-bus and 69-bus radial distribution system. Voltage stability has been significantly improved through the proper planning strategy of DGUs. Installing DGUs not only affects the losses and voltage profile, but it also affects harmonic distortions. Therefore, the authors in [8-9] have focused on the influence of harmonics under the integration of DGUs in the distribution system. Those authors used effective methods such as BBO and GSA for consideration for DGUs installation. After analyzing the effects of the DGUs, they concluded that the suitable siting and sizing of the DGUs can significantly reduce the harmonics in the distribution system. Like another aspect of the problem, recent researchers looked at the economic benefits of installing DGUs. [10-12] presented how to save investment, operation and maintenance costs through the optimal installation of DGUs by applying optimization algorithms as WCA, SQPT, ACO, etc. As shown, the total saving cost of DGUs is also a significant amount and this should be considered before integrating DGUs into the system. However, as shown reality shown, some grid integrated distributed generation systems that used fossil fuels have negative impacts on the natural environment. Consequently, studies in [12-13] have considered for reducing the impact on the environment through minimization of emission. By considering emission reduction as one of the objectives of the study, they have applied heuristic optimization algorithms for finding suitable solutions for DGUs installation to minimize emission. According to the development trend of the world to reduce the use of fossil fuels, the integration of renewable energy sources such as solar energy, wind energy, geothermal energy, etc are increasingly popular. Like the authors in [14] has researched on the connection of wind power generator by e-constraint method and the research in [15] has integrated wind-hydro-thermal systems for optimal scheduling by MASCSA. Although this integration can bring many benefits, once the distributed energy sources are integrated into the system, there should be careful consideration and avoidance of negative effects on the system. One of the main factors to consider is the power flow. It needs to be calculated carefully after the integration of DGUs into the system. This integration could break the configuration of the system if it were not imposed constraints of the branch current and the bus voltage, etc [8]. In this study, forward / backward sweep technique (FW / BWST) [16] is used to solve the power flow at the fundamental frequency and the harmonic flow at the high order frequency in the IEEE 85-bus radial distribution system. In this paper, distributed solar energy sources are considered for integration into the distribution grid for minimizing power loss under consideration of branch current, bus voltage and harmonics as constraints. Additionally, the coyote optimization algorithm (COA) [17] is proposed for solving optimization problems. COA is a powerful algorithm and it has recently been applied in finding the optimal solution for engineering and technology problems. Like [18], the authors proposed this algorithm to estimate the unknown parameters involved three various models of single, double and three diode models for photovoltaic modules and solar cells. Likewise, the authors in [19] have also suggested COA for solving the economic dispatch problem in the various integrated systems of thermal and wind generators. The obtained results also demonstrate the COA's superiority in finding better quality solutions than others. In general, COA and other heuristic algorithms such as MOGA [20], ACO [21], ALOA [22], etc are essentially methods by trial and error. They do not guarantee the best solution in the large search space. However, COA has outstanding and distinct properties as compared to others in the application and efficiency. COA has less control parameters than others and the COA's characteristics are easy to apply it to various optimization problems. Not only does COA create a balance during the exploration and exploitation phases, but it can also avoid local traps by expanding the search area. This has contributed to make it more proactive in finding the feasible solutions and improving the performance.

The main contributions to this study can be summarized as follows:
1) When integrating distributed photovoltaic units (PVUs) into the distribution system, the power loss, voltage profile, branch current, harmonics, etc can be changed dramatically. This change needs to be carefully analyzed. Hence, this study focuses on analyzing the effect of PVUs on distribution grid.
2) The benefits achieved from the grid integrated PVUs system are highly dependent on the used optimization method. Thus, recommending the method to optimize the considering problem is extremely important. This work proposes an efficiency algorithm with good stability and fast convergence speed, called the coyote optimization algorithm (COA) for minimizing power loss considering the branch current, voltage profile and harmonics in the IEEE 85-bus radial distribution system.
3) The location and capacity of PVUs have a great influence on economic and technical benefits. This study also demonstrated the role of determining the suitable installation of PVUs in the distribution system for maximum benefits.
The remainder of this paper can be divided into 5 parts. Part 2 is called the problem formulation. This part shows the objective function and constraints. Part 3 is named the proposed algorithm. It presents the application of the proposed algorithm for searching the optimal capacity and location of PVUs. Part 4 is the simulation results and discussion. This part presents the obtained results and analyzes the impact of PVUs in the IEEE 85-bus system. The rest is called conclusions. This part summarizes the entire main contents of the paper.

2. Problem Formulation

A. The objective function

Power loss reduction is a key factor in maximizing economic and technical benefits. Therefore, consideration for reducing the power loss in the distribution system is essential. In this paper, the authors have focused on minimizing power loss by determining the optimal location and capacity of PVUs. The main objective function (*ObF*) for minimizing power loss can be presented as Eq. 1 [23-24].

$$\text{Minimize } ObF=\sum_{b=1}^{N_{bra}} I_{bPVU}^{2} \times R_b \tag{1}$$

B. Constraints

1. The power balance constraints

Realistically, the total power generation should cover the total power loss on the transmission line and the total load demand in the system. Thus, the power balance equation after connecting PVUs can be expressed by [8]:

$$P_{gri}=\sum_{l=1}^{N_{loa}} P_{loa,l}+\sum_{b=1}^{N_{bra}} P_{los,b}-\sum_{p=1}^{N_{pvu}} P_{PVU,p} \tag{2}$$

2. The branch current constraints

In order to ensure that the transmission line structure is not changed, when connecting any generator into the grid, it is necessary to consider the allowable branch current limit. The branch current magnitude should be within the limit as [4]:

$$I_b \leq I^{\max},\ b=1,2,...,\ N_{bra} \tag{3}$$

3. The bus voltage limits

To keep the system running stably, the voltage profile should be within an acceptable limit. In other words, the bus voltage at the fundamental frequency should be maintained in constraints [25-27]:

$$V^{\min} \leq |V_{bu}| \leq V^{\max},\ bu=1,2,...,N_{bu} \tag{4}$$

4. The sizing limits of PVUs

The allowable capacity limit of each PVU should be determined before integrating into the system and total capacity of PVUs should not exceed the load demand. In this case, the total generating power is limited to 80% of the load demand. So, the sizing of PVUs should obey the constraints as below [28]:

$$\sum_{p=1}^{N_{pvu}} P_{PVU,p} \leq 80(\%) \times P_{loa} \tag{5}$$

$$P_{PVU}^{\min} \leq |P_{PVU,p}| \leq P_{PVU}^{\max} \tag{6}$$

5. The harmonic voltage distortion constraints

One of the key factors in evaluating power quality is the level of harmonic distortions. Hence, consideration of mitigating the harmonics to the permissible limit is important. The two values that are used to measure the harmonic level should be within the limits as Eq. 7 and Eq. 8.
The total harmonic voltage distortion should be kept according to Std. 519 [25]

$$THD_{V,bu}(\%) = \left[\frac{\sqrt{\sum_{h\neq 1}^{H}\left|V_{bu}^{h}\right|^{2}}}{\left|V_{bu}^{1}\right|}\right] \times 100 \leq THD^{\max}(\%) \tag{7}$$

As shown above equation, the total harmonic voltage distortion at the bu^{th} bus ($THD_{V,bu}$) is calculated as the quotient between the square root of the sum of the squares of the bus voltage magnitude at the higher order frequency (V_{bu}^{h}) and the bus voltage magnitude at the fundamental frequency (V_{bu}^{1}). This value in percent should not exceed the maximum allowed limit (THD^{max}).
Similarly, the individual harmonic distortion should also be kept according to Std. 519 [25]

$$IHD_{V,bu}^{h}(\%) = \left[\frac{\left|V_{bu}^{h}\right|}{\left|V_{bu}^{1}\right|}\right] \times 100 \leq IHD^{\max}(\%) \tag{8}$$

Where, $IHD_{V,bu}^{h}$ is defined as the individual harmonic voltage distortion at the bu^{th} bus at the higher order frequency and this value in percent should not exceed the maximum allowed limit (IHD^{max}).

3. The Proposed Method

In this paper, COA is the proposed method for optimizing the position and capacity of PVUs in the 85 buses distribution system. COA is a new approach that has been developed based on the nature behaviors of the coyote community. In COA, the social condition and the social condition quality become the two main elements that characterize for each coyote. Social condition quality corresponds to the fitness of the solution and social quality corresponds to the optimal solution. The process of applying COA for solving the optimization problem is briefly presented as follows [17]:

Step 1: In COA, the population (N_{po}) consists of two components: the coyote numbers in each group (N_c) and the group numbers in the coyote community (N_g). Thus, investigation and selection of initial parameters such as N_g, N_c and $Iter^{max}$ are the task in this step.

Step 2: Generate the initial solution and evaluate the initial solution: In this step, the initial solutions are generated randomly by using Eq. (9) within the predetermined range of [So^{max} and So^{min}]. Each created solution is evaluated by using an objective function as Eq. (10) and the number of iterations to be counted with the initial iteration equals 1 (*Iter*=1)

$$So_{c,g}=So^{\min}+r\times\left(So^{\max}-So^{\min}\right);\ c=1,\dots,N_c\ \&\ g=1,\dots,N_g \tag{9}$$

$$Fit_{c,g}=OPF_{c,g}+\lambda_{IP}\times\sum_{b=1}^{N_{bra}}\Delta IP_{b,c,g}+\lambda_{VP}\times\sum_{bu=1}^{N_{bus}}\Delta VP_{bu,c,g}+\lambda_{HP}\times\left(\sum_{bu=1}^{N_{bus}}\Delta THP_{bu,c,g}+\sum_{bu=1}^{N_{bus}}\Delta IHP_{bu,c,g}\right) \tag{10}$$

Where $\Delta VP_{bu,c,g}$, $\Delta IHP_{bu,c,g}$, $\Delta THP_{bu,c,g}$ are the penalty terms for violations from the voltage, the individual harmonic distortion and total harmonic distortion at the bu^{th} bus corresponding to the c^{th} solution in the g^{th} group; $\Delta IP_{b,c,g}$is the penalty term for current violation on the b^{th} branch corresponding to the c^{th} solution in the g^{th} group. These terms are determined as follows:

$$\Delta IP_{b,c,g}=\begin{cases} I_{b,c,g}-I_b^{\max} & if\ I_{b,c,g}>I_b^{\max} \\ I_b^{\min}-I_{b,c,g} & if\ I_{b,c,g}<I_b^{\min} \\ 0 & else \end{cases} \tag{11}$$

$$\Delta VP_{bu,c,g}=\begin{cases} V_{bu,c,g}-V^{\max} & if\ V_{bu,c,g}>V^{\max} \\ V^{\min}-V_{bu,c,g} & if\ V_{bu,c,g}<V^{\min} \\ 0 & else \end{cases} \tag{12}$$

$$\Delta THP_{bu,c,g}=\begin{cases} THP_{bu,c,g}-THD^{\max} & if\ THP_{bu,c,g}>THD^{\max} \\ 0 & else \end{cases} \tag{13}$$

$$\Delta IHP_{bu,c,g}=\begin{cases} IHD_{bu,c,g}-IHD^{\max} & if\ IHP_{bu,c,g}>THD^{\max} \\ 0 & else \end{cases} \tag{14}$$

Step 3: Collect the results and determine the best current solution ($So_{best,g}$) and the center solution ($S_{cent,g}$) in the each group. Generate the new solutions by using Eq. (15)

$$So_{c,g}^{new}=So_{c,g}+r_1\times\left(So_{best,g}\text{-}So_{rd1,g}\right)+r_2\times\left(S_{cent,g}\text{-}S_{rd2,g}\right);\ c=1,\dots,N_c\ \&\ g=1,\dots,N_g \tag{15}$$

Step 4: Each generated control variable $SV_{v,c,g}^{new}$ in each new solution are checked and kept within the allowed limits as Eq. (16)

$$SV_{v,c,g}^{new}=\begin{cases} SV_v^{min} & if\ SV_{v,c,g}^{new}<SV_v^{min} \\ SV_v^{max} & if\ SV_{v,c,g}^{new}>SV_v^{max} \\ SV_{v,c,g}^{new} & else \end{cases};\ v=1,\dots,N_v, c=1,\dots,N_c; g=1,\dots,N_g \tag{16}$$

After making correction for the new solutions, all solutions should be evaluated by using the objective function as Eq. (10)

Step 5: Save the good solutions by using the Eqs. (17) and (18)

$$So_{c,g}=\begin{cases} So_{c,g}^{new} & if\ FF_{c,g}^{new}<FF_{c,g} \\ So_{c,g} & else \end{cases} \tag{17}$$

$$Fit_{c,g}=\begin{cases} Fit_{c,g}^{new} & if\ Fit_{c,g}^{new}<Fit_{c,g} \\ Fit_{c,g} & else \end{cases} \tag{18}$$

Step 6: Find the worst solution and generate a new solution in each group by using Eq. (19)

$$SV_{v,g}^{new}=\begin{cases} CV_{v,r1,g} & if\ r<P_1 \\ CV_{v,r2,g} & if\ r<P_1+P_2 \\ CV_{v,rd} & otherwise. \end{cases} \tag{19}$$

Where

$$P_1=\frac{1}{N_v}\ \&\ P_2=\frac{1-P_1}{2} \tag{20}$$

The created new solution should be corrected by applying Eq. (19) and evaluate the new solution by using the objective function.

Step 7: The new solution is compared to the worst solution for selecting the better one.
Step 8: Swap the solutions between the selected groups if the condition in Eq. (21) is satisfied.

If it is not satisfied, move to step 9.

$$P_2<0.005\times N_c^2 \tag{21}$$

Step 9: Determine the best solution ($So_{c,g}^{new}$) in the current iteration and check the criteria for stopping iteration as Eq. (22)

$$Iter=Iter^{max} \tag{22}$$

If the criterion is not met, the number of the current iteration (*Iter*) is plus one unit and repeat step 3.

4. The Simulation Results

In this study, three PVUs are considered for optimal connection to the distribution system by using global optimization algorithm (COA). The results of COA are compared with two other positive methods, PSO and SSA. For all three implemented methods, the location for installation of PVUs in the IEEE 85-bus radial distribution system will vary from bus No. 2 buses. 85, bus No.1 is the slack bus. Meanwhile, the capacity of each PVU will vary in the predefined range of [0.0, 2.0] (MW). After conducting the survey, the maximum number of iterations ($Iter^{max}$) for each trial run is 250 and the total number of trial runs (R^{max}) with the initial population randomly distributed is 60 times. All simulations are performed by MATLAB in the personal computer (RAM: 8.0 GB and Processor: 1.8 GHz). The parameters for the three implemented methods are shown below:

For COA, the population number is defined as the product of the coyote numbers (N_c) and the group numbers (N_g) and this value affects the performance of the algorithm. Therefore, N_c and N_g values should be surveyed to choose the appropriate parameter. In this case, the selected value of N_c is 4, 5 and 6 for the combination with 6, 5, and 4 of N_g, respectively. Survey results have shown that the values of N_c and N_g are chosen to be the same and equal to 5 to get the optimal solution better than the other pairs.

For PSO, the two acceleration elements (C_I and C_{II}) contribute to the quality of solution. Thus, (C_I and C_{II}) have been investigated for the optimal selection by previous research [8] and they are chosen by 2. Besides, the minimum value and maximum value of the inertia weight factors (W^{min} and W^{max}) are set to 0.4 and 0.9, respectively. These values are appropriate and often used when applying PSO for solving the optimization problem. Additionally, the population number (N_{po}) in this algorithm is chosen to be 30 to facilitate the comparison.

In the SSA algorithm, the coefficient C_I is an extremely important parameter and significantly affects the quality of the solution because this value balances between the exploration and exploitation phases. Like research [29] has shown, C_I can be taken from the function of $2e^{-\left(\frac{4Iter}{Iter^{max}}\right)^2}$. Besides, two coefficient values, C_{II} and C_{III} are also randomly produced in the range from 0 to 1. For fair evaluation, N_{po} value in this algorithm is set to the same as PSO.

In this system, the voltage limits (V^{max} and V^{min}) at the fundamental frequency are set in the best range of [0.95 1.05] (pu) [30]. Besides, the harmonic flows with the detailed information is taken from [8, 31] are injected simultaneously into the system on buses such as bus No. 6, 18, 31, 43, 57, 67 and 75 with the maximum harmonic limits of THD^{max} and IHD^{max} equal 5% and 3%, respectively [32].

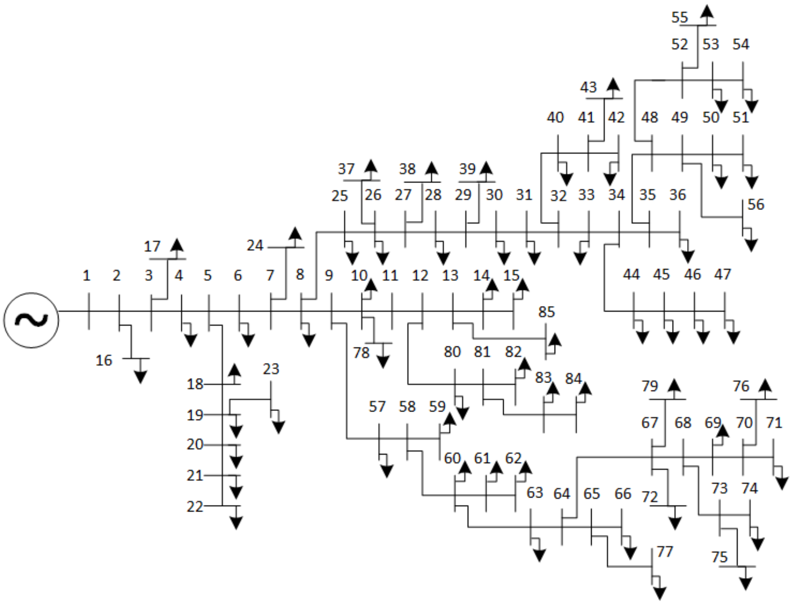

Figure 1. IEEE 85-bus radial distribution system

Figure 1 shows the structure of the 85 buses systems. The system has 85 buses (bus 1 is assigned as the slack bus), the power loss is 0.3161 MW, the active power and reactive power load demand of 2.5703 MW and 2.6221 MVar, respectively. Besides, the bus data and line data of IEEE 85-bus radial distribution system are taken from [33].

As mentioned, the main objective function of this paper is to find solutions for the position and capacity of three PVUs by using optimization algorithms. Due to the characteristics of the algorithm, the initial population can affect the solution. To avoid this, 60 trial runs are conducted with the initial population randomly generated. The results of the fitness values from COA, SSA and PSO are plotted as Figure 2.

In this study, heuristic algorithms have been selected for solving the optimization problem. Due to the stochastic characteristic of the algorithms, it is difficult for them to guarantee finding the best optimal solution. Hence, 60 trial runs with 250 iterations per each trial time are performed. The results obtained are presented in Table 1. In this table, the mean fitness of each method is calculated based on the best results of the fitness function in the 60 trial runs. The calculation of this value is used as a basis for evaluating the stability of implemented methods. Besides, for the fair comparison, the best value and the worst value of the 60 trial runs are also collected.

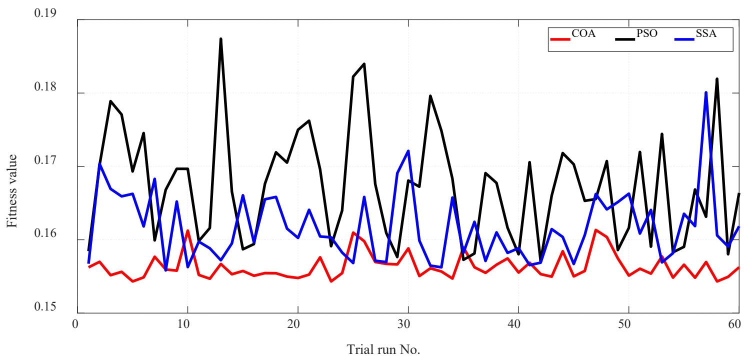

Figure 2. The fitness values of implemented methods in 60 trial runs

Table 1. The best fitness, the average fitness and the worst fitness values of PSO, SSA and COA in 60 trial runs

Method	PSO	SSA	COA
The best fitness	0.1571	0.1558	0.1543
The mean fitness	0.1673	0.1617	0.1563
The worst fitness	0.1874	0.1801	0.1613

In this case, the stability representation of each method is the mean fitness and the smaller this value, the more stable it will be. The best fitness and the average fitness values of PSO, SSA, and COA are 0.1571 and 0.1673, 0.1558 and 0.1617, and 0.1543 and 0.1563, respectively. Clearly, the best fitness values and the average fitness value of COA are lowest as compared. This indicates that COA can propose the feasible solutions with the best quality and stability compared to other methods. Besides, the worst value of COA, 0.1613 is also lower than the worst values of PSO and SSA, 0.1874 and 0.1801, respectively. These collected results also contribute to reinforce the above argument about the efficiency of the proposed method.

Table 2. The best solution of PSO, SSA and COA in 60 trial runs

Applied method	The optimal solution (Place – Size)	Power loss (MW)	Power loss reduction (%)
Without PVUs	-	0.3161	-
With PVUs by using PSO	Bus 66 – 0.2994 MW; Bus 58 – 0.9257 MW; Bus 48 – 0.7537 MW	0.1571	50.3005
With PVUs by using SSA	Bus 63 – 1.0312 MW; Bus 48 – 0.6278 MW; Bus 30 – 0.3513 MW	0.1558	50.7118
With PVUs by using COA	Bus 74 – 0.2433 MW; Bus 58 – 0.9987 MW; Bus 34 – 0.8141 MW	0.1543	51.1863

Table 2 shows the best solution for siting and sizing of PVUs that are proposed from the implemented methods in 60 trial runs. For each optimal solution, the power loss of the system is different. Without the connection of PVUs, the power loss is 0.3161 MW. However, when the optimal solution is applied into the system, the power loss is significantly reduced. Specifically, COA's power loss is the smallest, 0.1543 MW, while power loss of PSO and SSA are 0.1571 MW and 0.1558 MW, respectively. Corresponding to each found power loss value after the PVUs' connection to the system, the power loss reduction in percent is calculated. This value represents the level of the system loss reduction after the optimal solution is applied. The larger this value, the higher the performance of the algorithm. As shown in Table 2, COA's power loss reduction, 51.1863 % is larger than PSO and SSA, 50.3005 % and 50.7118 %, respectively. Thereby shows that the optimal solution found by COA has better quality than others. Summary, the selection of the optimization algorithm that has high efficiency and stability for determining the optimal planning strategy for PVUs is extremely important in maximizing benefits and COA is the best choice in this case.

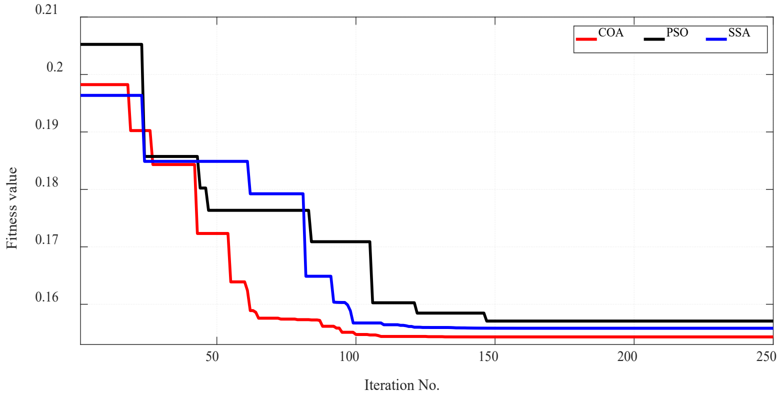

Figure 3. The convergence characteristics of implemented methods in 250 iterations

The convergence characteristics of the methods within the 250 iterations of the best solution are shown in Figure 3. The COA seems to have found better potential solutions than the others in the early stage, 25th iteration and COA converges quite quickly compared to PSO and SSA.

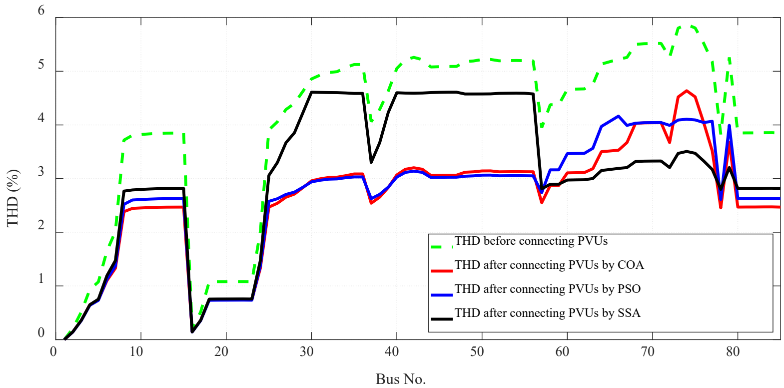

Figure 4. The total harmonic distortion before and after connecting PVUs

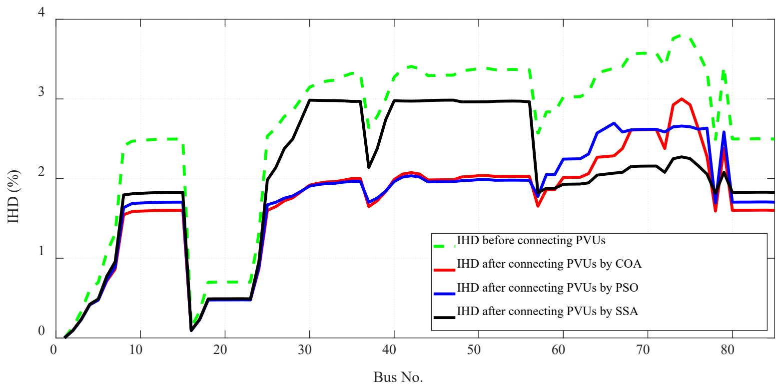

Figure 5. The individual harmonic distortion before and after connecting PVUs

Figure 4 and 5 show total harmonic voltage distortions (*THDv*) as well as individual harmonic voltage distortion (*IHDv*) before and after connecting PVUs by using PSO, SSA and COA. Before connecting PVUs, *THDv* values at many buses in the system are higher than the allowed limits of Std. 519 with the highest *THDv* and *IHDv* values equal to 5.8719 % and 3.8038 %, respectively. However, after connecting three PVUs, both *THDv* and *IHDv* values at all buses decrease and those values are within the allowable limits as shown in Figure 4. It has been proven that proper position and capacity of PVUs can mitigate harmonics in the distribution system.

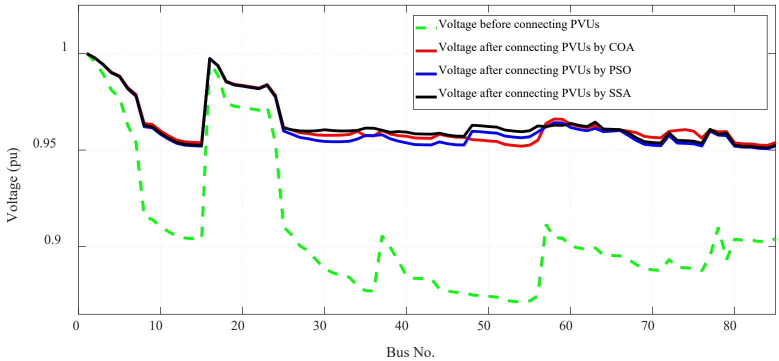

Figure 6. The voltage profile of PSO, SSA và COA before and after connecting PVUs

Before PVUs are integrated into the system, the lowest value of the bus voltage is 0.8713 pu. This value is lower than the setting voltage range, [0.95 1.05] pu. However, after connecting PVUs, the voltage profile has improved significantly. All bus voltage values are within the setting limits as Figure 6. This shows the benefit of enhancing the quality of the voltage when connecting the PVUs properly.

In summary, the above analysis has demonstrated the effectiveness of COA in proposing better quality solution as compared to others in 85 buses systems. All implemented methods have been considered under constraints such as power balance, bus voltage limits, branch current limits, harmonic limits and power generation limits for fair comparison of performance and applicability to solve optimization problems. In this case, the iteration number and the number of trial runs have been set as constants, so they do not take into consideration. As shown, it is clear that the convergence from COA is better than the others due to the less number of control parameters in the algorithm. Specifically, in PSO, this algorithm has four control parameters, including C_I, C_{II}, W^{max} and W^{min}. These four parameters can transform to enhance its performance. In SSA, it has a total of three control parameters, C_I, C_{II} and C_{III}. Similar to PSO, these three control parameters also contribute primarily to improve the performance of the algorithm. Finally, the proposed method, COA has only two control parameters that can be changed their values to improve efficiency, N_c and N_p. If the sum of the combination of control parameters is calculated as the factorial of the number of control parameters, COA value is the smallest as compared and equal to 2, while PSO and SSA are 24 and 6, respectively. Due to the simple in the configuration of COA, it does not require multiple testing to adjust parameters as compared algorithms. This results in less time consuming and faster convergence speed than others. By combining the above arguments and the obtained results from the simulation, all prove why the convergence, time-consuming and efficiency of COA are better than SSA and PSO.

5. Conclusions

In this paper, COA together with PSO and SSA is performed for searching the optimal siting and sizing for PVUs in an IEEE 85-bus radial distribution system. The aim of the study is to minimize the power loss with consideration of many constraints as the bus voltage, the harmonics, the branch current and the penetration of PVUs in the system. The results obtained from connecting three PVUs by COA have shown that the power loss has decreased significantly from 0.3161 MW to 0.1543 MW, corresponding to 51.1863% in power loss reduction. This is the best result compared to other methods such as PSO and SSA. Besides, all bus voltage values are drastically improved and within the best range between 0.95 pu and 1.05 pu. In addition, the harmonic distortions are also mitigated. Thanks to the proper connection of PVUs, the values of

THDv and *IHDv* are brought to the allowable limits of 5% and 3%, respectively. The collected data showed that COA not only has good performance, but also has high stability and relatively fast convergence speed. In short, COA is really a powerful method in solving optimization problems.

6. References

[1]. T.T. Nguyen, "Enhanced sunflower optimization for placement distributed generation in distribution system," *International Journal of Electrical and Computer Engineering*, vol.11(1), pp. 107, 2021

[2]. T.R. Ayodele, A.S.O. Ogunjuyigbe, O.O. Akinola, "Optimal location, sizing, and appropriate technology selection of distributed generators for minimizing power loss using genetic algorithm," *Journal of Renewable Energy*, 2015.

[3]. A. Soumya, A. Amudha, "Optimal Location and Sizing Of Distributed Generators In Distribution System," *International Journal of Engineering Research & Technology (IJERT)*, vol. 2(2), 2013.

[4]. K. Bhumkittipich, W. Phuangpornpitak, "Optimal placement and sizing of distributed generation for power loss reduction using particle swarm optimization," *Energy Procedia*, vol. 34, pp. 307-317, 2013.

[5]. S. Devi, M. Geethanjali, "Optimal location and sizing determination of Distributed Generation and DSTATCOM using Particle Swarm Optimization algorithm," *International Journal of Electrical Power & Energy Systems*, vol. 62, pp. 562-570, 2014.

[6]. M.C.V. Suresh, E.J Belwin, "Optimal DG placement for benefit maximization in distribution networks by using Dragonfly algorithm," *Renewables: Wind, Water, and Solar*, vol. 5(1), pp. 1-8, 2018.

[7]. N. Mohandas, R. Balamurugan, L. Lakshminarasimman, "Optimal location and sizing of real power DG units to improve the voltage stability in the distribution system using ABC algorithm united with chaos," *International Journal of Electrical Power & Energy Systems*, vol. 66, pp. 41-52, 2015.

[8]. M.Q. Duong, T.D. Pham, T.T. Nguyen, A.T. Doan, H.V. Tran, "Determination of optimal location and sizing of solar photovoltaic distribution generation units in radial distribution systems," *Energies*, vol. 12(1), pp. 174, 2019.

[9]. A.F.A. Kadir, A. Mohamed, H. Shareef, M.Z.C. Wanik, A.A. Ibrahim, "Optimal sizing and placement of distributed generation in distribution system considering losses and THDv using gravitational search algorithm," *Przeglad Elektrotechniczny*, vol. 4, pp. 132, 2013

[10]. B.H. Dinh, T.T. Nguyen, T.T. Nguyen, T.D. Pham, "Optimal location and size of photovoltaic systems in high voltage transmission power networks," *Ain Shams Engineering Journal*, pp. 1-20, 2021.

[11]. M.A. El-Sayed, M.A. Alsaffar, "Two stage methodology for optimal siting and sizing of distributed generation in medium voltage network," *In 2016 IEEE Green Technologies Conference (GreenTech)*, pp. 118-123, 2016.

[12]. T. Bahar, O. Singh, V. Yadav, "Optimal planning strategies of DG in distribution systems. In Applications of Computing," *Automation and Wireless Systems in Electrical Engineering, Springer, Singapore*, pp. 333-345, 2019.

[13]. H. A Abd El-Ghany, A.M. Azmy, M. Saad, "Optimal DG Deployment Based on Technical and Economic Considerations with Daily Load Variation," *In International Journal of Engineering Research in Africa*, vol. 45, pp. 115-131, 2019.

[14]. A. H. Shojaei, A. A. Ghadimi, M. R. Miveh, F. Mohammadi, F. Jurado, "Multi-objective optimal reactive power planning under load demand and wind power generation uncertainties using ε-constraint method," *Applied Sciences*, volt. 10, pp.1-30, 2020.

[15]. T. T. Nguyen, L. H. Pham, F. Mohammadi, L. C. Kien, "Optimal scheduling of large-scale wind-hydro-thermal systems with fixed-head short-term model," *Applied Sciences*, vol. *10*, pp. 1-22, 2020.

[16]. J.H. Teng, C.Y. Chang, "Backward/forward sweep-based harmonic analysis method for distribution systems," *IEEE Transactions on Power Delivery*, vol. 22(3), pp. 1665-1672, 2007
[17]. J. Pierezan, L.D.S. Coelho, "Coyote optimization algorithm: a new metaheuristic for global optimization problems," *In 2018 IEEE congress on evolutionary computation (CEC)* pp. 1-8 2018
[18]. A. A. Z. Diab, H. M. Sultan, T. D. Do, O. M. Kamel, M. A. Mossa, "Coyote optimization algorithm for parameters estimation of various models of solar cells and PV modules," *IEEE Access*, *pp.1-9*, 2017.
[19]. U. Güvenç, E. Kaymaz, "Economic dispatch integrated wind power using coyote optimization algorithm," *In 2019 7th international Istanbul smart grids and cities congress and fair (ICSG), IEEE*, pp. 179-183, 2019.
[20]. T.T. Nguyen, F. Mohammadi, "Optimal placement of TCSC for congestion management and power loss reduction using multi-objective genetic algorithm," Sustainability, vol. 12, pp.1-15, 2020.
[21]. A. A. Ogunsina, M. O. Petinrin, Petinrin, E. N. Offornedo, J. O. Petinrin, G.O. Asaolu, "Optimal distributed generation location and sizing for loss minimization and voltage profile optimization using ant colony algorithm," *SN Applied Sciences*, vol. 3, pp. 1-10, 2021.
[22]. E. S. Ali, S. M. Abd Elazim, A. Y. Abdelaziz, "Ant Lion Optimization Algorithm for optimal location and sizing of renewable distributed generations," *Renewable Energy*, vol. 101, pp.1311-1324, 2017.
[23]. S.K. Injeti, V.K. Thunuguntla, "Optimal integration of DGs into radial distribution network in the presence of plug-in electric vehicles to minimize daily active power losses and to improve the voltage profile of the system using bio-inspired optimization algorithms," *Protection and Control of Modern Power Systems*, vol. 5(1), pp.1-15, 2020.
[24]. Y. Latreche, H.R. Bouchekara, M.S. Javaid, M.S. Shahriar, A.Yusuf, F. Kerrour, "Optimal Siting and Sizing of DG Units Using a Decomposition Based Multiobjective Evolutionary Algorithm," *In International Conference in Artificial Intelligence in Renewable Energetic Systems, Springer*, Cham. pp. 521-532, 2020.
[25]. A. Parizad, A.H. Khazali, M. Kalantar, "Siting and sizing of distributed generation through Harmony Search Algorithm for improve voltage profile and reduction of THD and losses," *In CCECE 2010 IEEE.* pp. 1-7, 2010, May.
[26]. A.S. Hassan, Y. Sun, Z. Wang, "Multi-objective for optimal placement and sizing DG units in reducing loss of power and enhancing voltage profile using BPSO-SLFA," *Energy Reports*, vol. 6, pp.1581-1589, 2020.
[27]. P.D.P. Reddy, V.V. Reddy, T.G. Manohar, "Whale optimization algorithm for optimal sizing of renewable resources for loss reduction in distribution systems," *Renewables*: wind, water, and solar, vol. 4(1), pp. 1-13, 2017.
[28]. S.K. Dash, L.R. Pati, S. Mishra, P.K. Satpathy, "Multi-objective Optimal Location and Size of Embedded Generation Units and Capacitors Using Metaheuristic Algorithms," *In Green Technology for Smart City and Society, Springer, Singapore*, pp. 471-486, 2021.
[29]. S. Mirjalili, A.H. Gandomi, S.Z. Mirjalili, S. Saremi, H. Faris, S.M. Mirjalili, "Salp Swarm Algorithm: A bio-inspired optimizer for engineering design problems," *Advances in Engineering Software*, vol. 114, pp. 163-191, 2017.
[30]. S.R. Gampa, D. Das, "Optimum placement and sizing of DGs considering average hourly variations of load," *International Journal of Electrical Power & Energy Systems*, vol. 66, pp. 25-40, 2015.
[31]. Github website. (2014). "Harmonic flows. Available online at https://github.com/tshort/OpenDSS/blob/master/Test/indmachtest/Spectrum.DSS
[32]. H. HassanzadehFard, A. Jalilian, "Optimal sizing and location of renewable energy based DG units in distribution systems considering load growth," *International Journal of Electrical Power & Energy Systems*, vol. 101, pp. 356-370, 2018.

[33]. D.B. Prakash, C. Lakshminarayana. “Optimal siting of capacitors in radial distribution network using whale optimization algorithm”, *Alexandria Engineering Journal*, vol. 56, pp. 499-509, 2017.

Van Duc Phan received his M.S. degree in Department of Electric, Electrical and Telecommunication Engineering from Ho Chi Minh City University of Transport, Ho Chi Minh, Vietnam and Ph.D. degree in Department of Mechanical and Automation Engineering, Da-Yeh University, Taiwan in 2016. Currently, he is a research interests are in sliding mode control, non-linear systems or active magnetic bearing, flywheel store energy systems, power system optimization, optimization algorithms, and renewable energies, Energy harvesting (EH) enabled cooperative networks, Improving the optical properties, lighting performance of white LEDs, Energy efficiency LED driver integrated circuits, Novel radio access technologies, Physical security in communication network, Simultaneous wireless information and power transfer for cognitive radio. He has published over twenty papers including higher than ten ISI papers.

Minh Quan Duong received his B.E. (2008) in Electrical Engineering Department at the University of Danang, University of Science and Technology, Vietnam, and M.S. (2012) degrees in Electrical Engineering at Dongguk University, Seoul, South Korea; and Ph.D. degree (2016) in Electrical Engineering at Politecnico di Milano, Milan, Italy. He has published over sixty papers including higher than thirty ISI/Scopus papers. His research interests include Renewable Energy in Power system and Planning.

Man Minh Doan received B.E. in control and automation technology from Thu Duc College of Technology, Ho Chi Minh City, Vietnam in 2021. Recently, he has successfully completed and won the high award in the work skills contest for engineering students in Ho Chi Minh City, 2020. Currently, he is working as a research assistant for a scientist in Viet Nam. His favorite research areas include renewable energies, artificial intelligence and automatic system simulation.

Thang Trung Nguyen received his M.Sc. and Ph.D degree in electrical engineering from Ho Chi Minh City University of Technology (HCMUT), in 2010 and 2018 respectively, Vietnam. Currently, he is a research and head of power system optimization research group at Faculty Electrical and Electronics Engineering, Ton Duc Thang university. He has published over sixty papers including higher than thirty ISI papers. His research fields are power system optimization, optimization algorithms, and renewable energies.