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Technical-Economic Indices for Optimal Integration of Photovoltaic Distributed Generation Units Using Hybrid PSO-WOA Technique

Samir Settoul[1*], Mohamed Zellagui [2], Rachid Chenni [1] and Nasreddine Belbachir [3]

[1]*Department of Electrotechnic, Mentouri University of Constantine 1, Constantine, Algeria.*
samir.settoul@umc.edu.dz; rachid.chenni@umc.edu.dz

[2]*Department of Electrical Engineering, University of Batna 2, Batna, Algeria.*
m.zellagui@univ-batan2.dz

[3]*Department of Electrical Engineering, University of Mostaganem, Mostaganem, Algeria.*
nasreddine.belbachir.etu@univ-mosta.dz

Abstract

This paper proposes to hybridize the Whale Optimizer (WOA) and Particle Swarm Optimization (PSO) algorithms to achieve optimal integration of Distributed Generator (DG) based photovoltaic sources in the search for optimal allocation. Optimal integration reduces the Active Power Loss (APL) index and enhances the Total Voltage Variation (TVV) index and the Total Operating Cost (TOC) index. The proposed hybrid PSO-WOA algorithm is validated on standard IEEE 33-bus and 69-bus Electrical Distribution Systems (EDS). Numerical and graphical comparative studies were conducted to benchmark the hybrid approach results against those obtained using other powerful algorithms and techniques existing in the literature. Active and reactive branch currents are calculated and plotted to show how the DG affects current flows in the EDS. To make the results more realistic, linear load level variation is considered, with the loads varying from 60% to 120% of the rated loading level.

Keywords: Optimal integration, solar photovoltaic energy, distributed generation, technical-economic indices, voltage variation, active power loss, operating cost, hybrid optimization technique, electric distribution system.

Introduction

The demand for electricity is rising consistently due to industrial development and urbanization. In response to climate concerns, there is a marked shift away from fossil-fuel based electric energy generation and toward renewables. This, in turn, raises major issues regarding integrating renewable energy sources in Electric Distribution Systems (EDS).

The optimal allocation and planning of DG based on renewable sources minimizes system losses of power, enhances the quality of voltage, and boosts power supply reliability. Therefore, many objective functions were devoted to maximizing the positive impacts of DG. In this context, most objectives addressed the minimization of Active Power Loss (APL), enhancement of voltage quality, and maximization of economic benefits [1].

The allocation (placement and size) of DG is mainly a complex, non-linear optimization problem [2]. Researchers have taken multiple approaches to determine the optimal integration of DG in EDS using many algorithms. Examples include: (i) using the Loss sensitivity factor with the Bacterial Foraging Optimization Algorithm (BFOA) to minimize APL, the costs of operation and enhance voltage stability [3], (ii) the Flower Pollination Algorithm (FPA) to reduce APL and improve bus voltage [4], (iii) the Particle Swarm Optimization (PSO) algorithm to solve both objective functions based on APL minimization and Voltage Stability Index (VSI) enhancement by single and multiple numbers of active and reactive powers from DG [5], (iv) the Krill Herd Algorithm (KHA) to reduce APL including maintaining the bus voltage and VSI [6], (v) the Invasive Weed Optimization (IWO) algorithm validated for various models of load including objective functions devoted to minimizing APL and operational cost and improving VSI [7], (vi) the Ant Lion Optimization (ALO) algorithm for single and multi-objectives addressing minimization of exchange cost of energy from enhanced network reliability, (vii) minimization of DGs' cost of application, APL and bus voltage deviation [8], (viii) the Adaptive Genetic Algorithm (AGA) including on-load tap changer to reduce APL and maximize bus voltage [9], (ix) the Symbiotic Organism Search (SOS) algorithm to reduce APL of EDS considering the loss sensitivity factor [10], (x) the Spider Monkey Optimization (SMO) algorithm to find the optimal DG to improve voltage security [11], and (xi) the Moth Flame Optimizer (MFO) algorithm to reduce APL and enhance EDS voltage stability [12].

Researchers are continuously adopting new combined algorithms, generally called: the hybrid optimization technique [13]. Various types of hybrid optimization algorithms were addressed in the literature: (i) determine sensitive nodes by the sensitivity factor and apply a hybrid HSA-ABC algorithm to minimize APL in EDS while improving bus voltage [14], (ii) use the AM-PSO algorithm to install multiple DGs to reduce APL and the bus voltage profile with the optimal power factor [15], (iii) use loss sensitivity analysis with a hybrid ABC-CS algorithm and obtain a new VSI to greatly enhance voltage stability and save power across the network [16], (iv) a hybrid GA-VSED algorithm with different scenarios to minimize APL and maximize voltage profile [17], (v) with conventional and renewable energy, a GWO-PSO algorithm to achieve maximum reduction of APL and improve voltage profile [18], (vi) hybridize BSA with fuzzy rule-based expert system (FES), called BSA-FES, for a multi-objective function to mitigate APL, consolidate static VSI, and improve voltage profiles [19], (vii) reconfiguration and installation of multi DG units by implementation of the PSO-CSA algorithm to reduce APL and enhance VSI [20], (viii) the WIPSO-GSA approach for the installation of DGs and capacitors to minimize apparent power losses and achieve economic benefit when considering the parameters of essential cost for the total period of planning [21], (ix) hybridization of WOA with SSA to minimize APL and solve TVV with the installation of multi-DG units [22], (x) using a novel weighted locational marginal price based method with a hybrid FA-PSO algorithm to relieve congestion in a competitive power market, including the objective of minimizing congestion cost [23], (xi) hybrid GWO with evolutionary algorithm operators (HGWO) based on WT and PC systems to achieve maximum reduction of APL, grid dependency and improve voltage stability [24], (xii) combination of fuzzy hybrid differential evolutionary and CSA algorithm (fuzzy DE-CSA) to reduce APL, total neutral current and TOC, while maximizing the average voltage deviation index [25], based on PVs and WTs (xiii) HTLBO-GWO for multi-objective function of loss reduction and improved reliability [26], (xiv) hybrid PSO-GSA algorithm with loss-sensibility-factors (LSFs) to minimize APL and TOC, while enhancing the voltage profile [27], and (xv) the GA-TOPSIS algorithm for stage multi-objective function for the installation of DGs and remote terminal units simultaneously with various scenarios such as different number of DG units and adaptive power factor for DG [28].

The hybrid PSO–WOA algorithm is a result of combining separate PSO and WOA. The hybrid algorithm combines the strengths of both algorithms: exploitation for PSO, and the exploration phase toward the targeted optimum solution for the WOA. WOA utilizes a function of logarithmic spiral, so it covers a broader area for uncertain space [29].

This paper presents the optimal installation of photovoltaic based distributed generation in radial distribution systems using the hybrid PSO-WOA algorithm. This study seeks to determine the optimal presence of renewable DG in two different standard EDS. The proposed hybrid optimization technique is superior to existing techniques and methods in terms of reducing the Active Power Loss (ΔAPL) index and enhancing the Total Voltage Variation (ΔTVV) index and the Total Operating Cost (ΔTOC) index.

Problem Formulation and Constraints

A. Objective Function

The developed objective function (OF) is devoted to mitigating the ΔAPL index and improving the ΔTVV index and ΔTOC index.

It represents a multi-objective function for the distribution system. The allocation DG is optimally obtained by:

$$OF = \min \sum_{i=1}^{Nbus}\sum_{j=2}^{Nbus} \gamma_1 \Delta APL_{ij} + \gamma_2 . \Delta TVV_i + \gamma_3 . \Delta TOC_{ij} \quad (1)$$

The indices are indicated in equations (2), (3) and (4) as follows:

$$\Delta APL = \frac{P_{Loss}^{After\ DG}}{P_{Loss}^{Before\ DG}} \quad \text{and} \quad P_{Loss} = \sum_{i=1}^{Nbus}\sum_{i=2}^{Nbus} R_{ij} \frac{(P_{ij}^2 + Q_{ij}^2)}{V_i^2} \quad (2)$$

$$\Delta TVV = \frac{TVV_{After\ DG}}{TVV_{Before\ DG}} \quad \text{and} \quad TVV = \sum_{i=2}^{Nbus} \left|1 - V_i\right| \quad (3)$$

The TOC is another merit of DG integration in distribution networks [3]. This cost is minimized while reducing the rate of real power drawn from the DGs. The Δ*TOC* index is obtained by:

$$\Delta TOC = \frac{TOC_{After\ DG}}{TOC_{Before\ DG}} \quad (4)$$

The TOC before and after the DG installation is represented by:

$$TOC_{Before\ DG} = K_2 \times P_{Loss}^{Before\ DG} \quad (5)$$

$$TOC_{After\ DG} = (K_1 \times P_{Loss}^{After\ DG}) + (K_2 \times P_{Loss}^{Before\ DG}) \quad (6)$$

B. Power conservation constraint

The mathematical representation of active and reactive power injected is given by [3-8], [30-33]:

$$P_G + P_{DG} = P_D + P_{Loss} \quad (7)$$

$$Q_G = Q_D + Q_{Loss} \quad (8)$$

Bus voltage limits:

$$V_{\min} \le \left|V_i\right| \le V_{\max} \quad (9)$$

Voltage drop limit:

$$\left|V_1 - V_i\right| \le \Delta V_{\max} \quad (10)$$

Line capacity constraint:

$$\left|S_{ij}\right| \le \left|S_{\max}\right| \quad (11)$$

C. DG constraints

Inequality constraints illustrate the limits of the DG unit [34, 33, 35], which are given as: DG capacity:

$$P_{DG}^{\min} \le P_{DG} \le P_{DG}^{\max} \quad (12)$$

Position of DG:

$$2 \le DG_{Position} \le N_{bus} \quad (13)$$

Number of DG:

$$N_{DG} \le N_{DG.\max} \quad (14)$$

Location of DG:

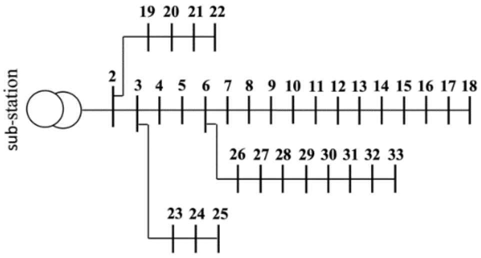
$$n_{DG,i} \,/\, Location \le 1 \quad (15)$$

TEST SYSTEMS, RESULTS, AND COMPARISON

The proposed hybrid PSO-WOA algorithm is implemented in a PC that has an Intel i5 processor, 2.7 GHz, and 8 GB RAM.

The first test system in this study is IEEE 33-bus, which is illustrated in Figure 1.a. It comprises 33 buses, and 32 lines of distribution [36].

Figure 1.b illustrates the second test system, IEEE 69-bus. It is composed of 69 buses, and 68 distribution lines. The base voltage of the two systems is 12.66 kV [37].



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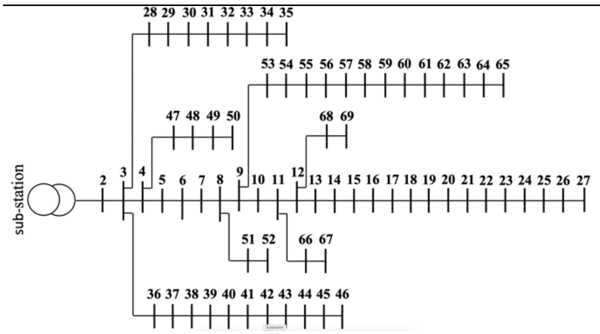
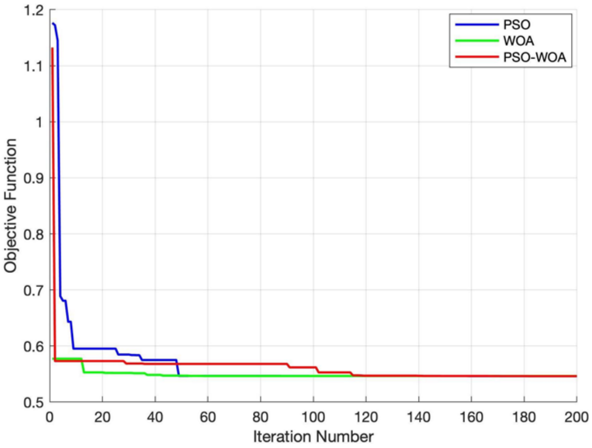


(b)

Figure 1: Single line diagram of EDS. a). IEEE 33-bus, b). IEEE 69-bus.

Figure 2 illustrates the convergence optimization characteristics of the applied algorithms for the two test systems with the optimal presence of DG.



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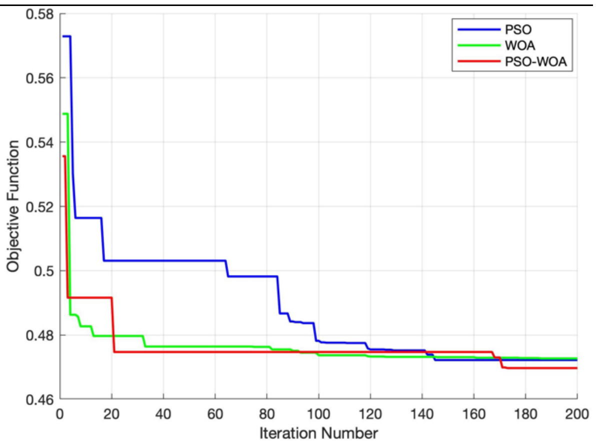


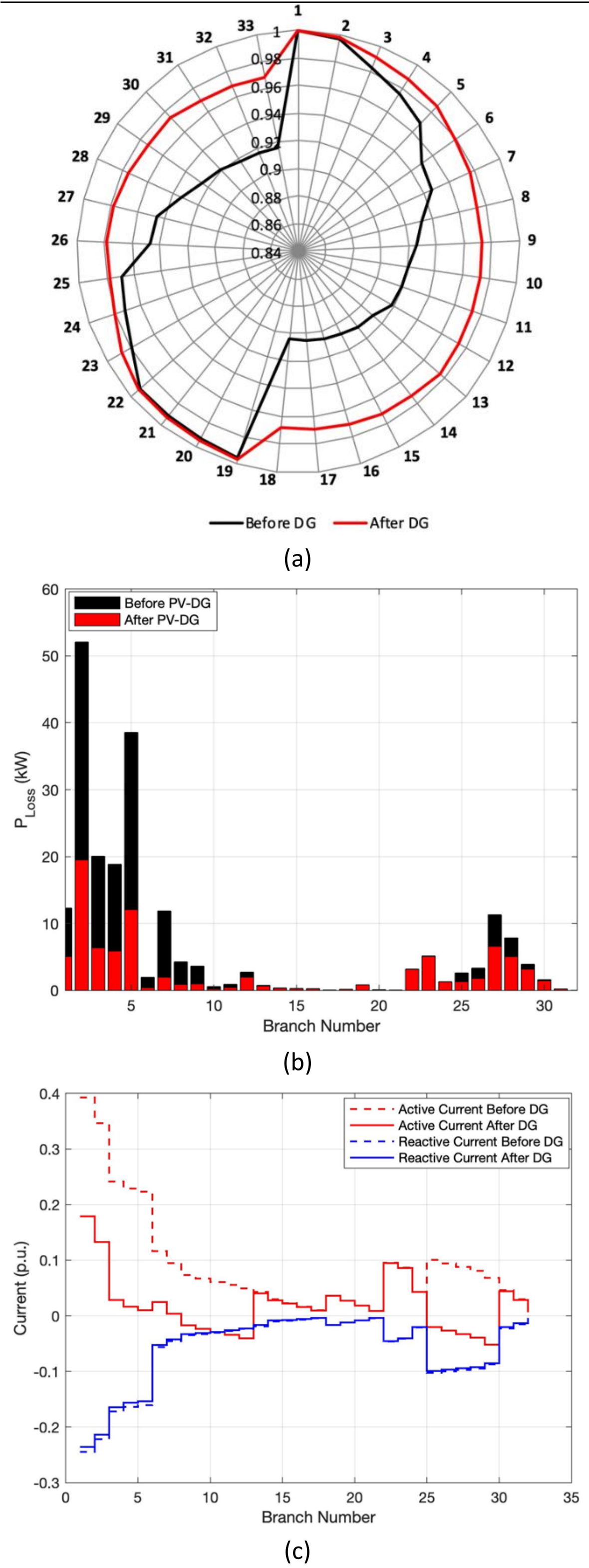
(b)

Figure 2: Convergence curve of various applied algorithms: a). IEEE 33-bus, b). IEEE 69-bus.

For the first test system, the IEEE 33-bus, the convergence curves show quick convergence to the optimal solution within the first 5 iterations for WOA and hybrid PSO-WOA, and convergence within the first 10 iterations. However, WOA and PSO take almost the same time to provide the optimal solution within 40-50 iterations, while PSO-WOA takes a longer time to obtain the optimal and the better solution among the algorithms within 110-120 iterations.

For the IEEE 69-bus, PSO-WOA takes a much longer time to achieve the better solution for about 170-180 iterations, whereas PSO takes between 140 to 150 to arrive at the optimal solution and WOA takes less time to converge, as it converges within 100 iterations.

Figures 3 and 4 indicate the comparison of the bus voltage profiles, the power losses, and the branch current before and after DG installation for the IEEE 33- and 69-bus systems respectively.

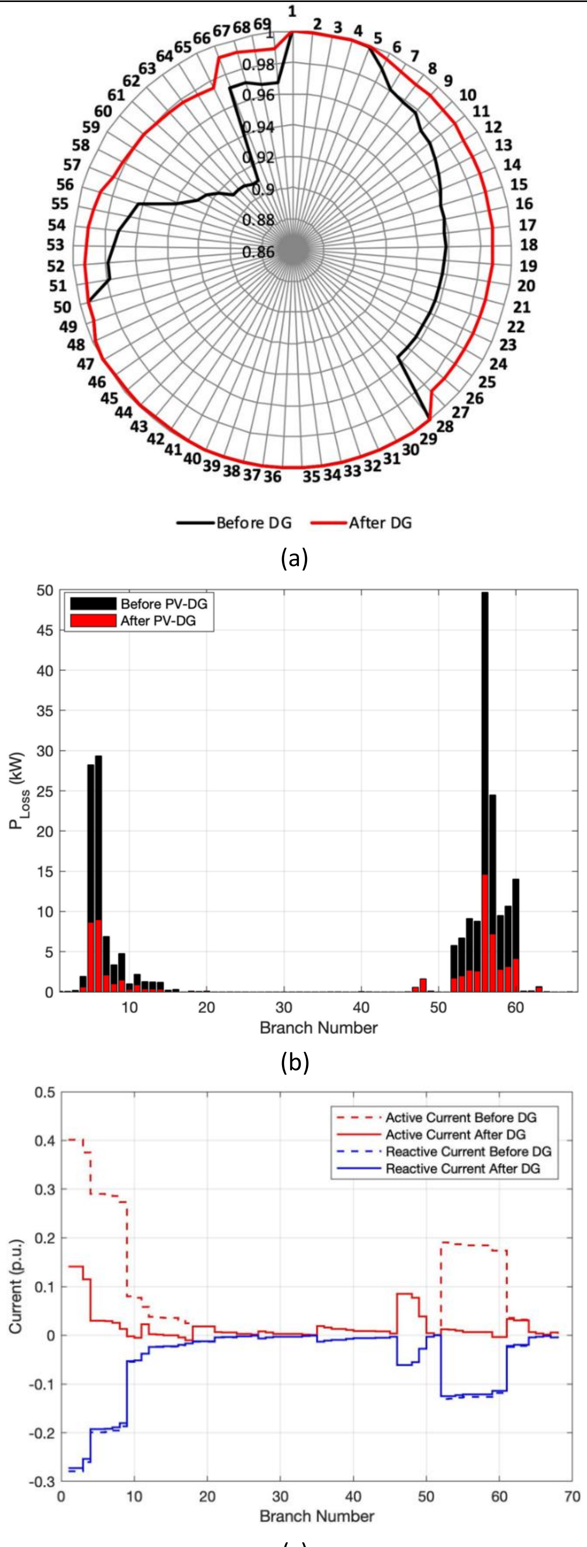


(a)

(b)

(c)

Figure 3: Optimal results of IEEE 33-bus: a). Bus voltage, b). Active power loss, c). Active and reactive current.



(a)

(b)

(c)

Figure 4: Optimal results of IEEE 69-bus: a). Bus voltage, b). Active power loss, c). Active and reactive current.

From Figures 3 and 4, it can be observed that there is a clear enhancement of the voltage profiles in the presence of DG; the constraints of voltage and voltage drop are satisfied, the voltage stays within limits and the voltage profiles are almost flat. The figures also illustrate the significant minimization of power losses due to the high amount of active power injected from the photovoltaic distributed generation units. It can be noted that the losses in some branches are near to zero. The same figures demonstrate the effectiveness of DG on the active and reactive current in the branches, as we can observe the active current in each branch has decreased significantly. The reactive current was little affected by the existence of DG, because there was no reactive power injected in the system. It can also be seen that the influence of DG on the current appears close to the locations where DG was installed; in general, the greatest amount of losses are found in these locations as well as currents.

The simulation results of the two EDS test systems for the base case (before DG) and optimization results after the presence of DG are set out in Table 1.

Table 1: Analysis of the performance of the proposed algorithm.

Test System	***IEEE 33-Bus***		***IEEE 69-Bus***	
Parameters	***Before DG***	***After DG***	***Before DG***	***After DG***
P_{Loss} (kW)	210.987	87.1656	224.948	69.8395
ΔP_{Loss} (%)	---	66.8987	---	68.9530
Q_{Loss} (kVar)	143.128	59.8145	102.140	35.1927
ΔQ_{Loss} (%)	---	75.4118	---	65.5446
V_{min} (p.u.)	0.9038	0.9685	0.9092	0.9759
ΔAPL (%)	—	33.1013	—	31.0470
ΔTVV (%)	—	55.1560	—	55.4053
ΔALC (%)	—	126.4810	—	124.8376

From Table 1, for IEEE 33-bus EDS, the power losses obtained using the power flow program before DG installation are 210.987 kW for active power losses and 143.128 kVar for reactive power losses. The optimization results show that the installation of DG greatly minimizes the active and reactive power losses to 87.1656 kW and 59.8145 kVar, by up to 66.8987 % and 75.4118 % respectively, and also clearly improves the voltage profile, with the minimum voltage enhanced from 0.9038 to 0.9685 p.u.

Table 1 shows the impact of the integration of DG on power losses and voltage profiles for IEEE 69-bus. As illustrated, APL is minimized by 68.9530 % from 224.948 to 69.8395 kW; the reactive power is minimized by 65.5446 % from 102.140 to 35.1927 kVar. The installation of DG led to a large improvement in the voltage profile and a significant minimization in the voltage drops; the minimum voltage reached 0.9759 p.u., where it was equal to 0.9092 p.u.

The results set out in this paper have been compared with other results obtained by different algorithms from the literature. The comparison, illustrated in Table 2, is done for the purpose of confirming the performance of the proposed algorithm in solving the problem of optimal presence of distributed generation for different systems.

Table 2: Results comparison of various algorithms.

Algorithms Applied	***Sizing kW, Location***	***P_{Loss} (kW)***	***ΔP_{Loss} (%)***	***V_{min} (p.u.)***
IEEE 33-Bus				
FPA [4]	1001.40 (12) 1141.70 (30)	89.200	57.7226	0.9675
KHA [6]	824.48 (13) 1241.71 (29)	87.426	58.5634	0.9667
PSO-IA [15]	830.00 (13) 1110.00 (30)	87.280	58.6326	0.9667
BSA-FES [19]	1126.00 (13) 730.00 (30)	93.390	55.7367	0.9631
WIPSO-GSA [21]	850.00 (13) 1140.00 (30)	87.180	58.6800	0.9679
PSO-WOA	852.70 (13) 1158.00 (30)	87.165	58.6868	0.9685
IEEE 69-Bus				
IWO [7]	123.81 (27) 433.40 (65) 1326.60 (61)	74.590	66.8412	0.9802
AGA [9]	272.00 (12) 310.00 (21) 1861.00 (61)	70.669	68.5843	0.9820
GA-TOPSIS [28]	441.00 (18) 1110.00 (61)	73.59	67.2858	0.9734

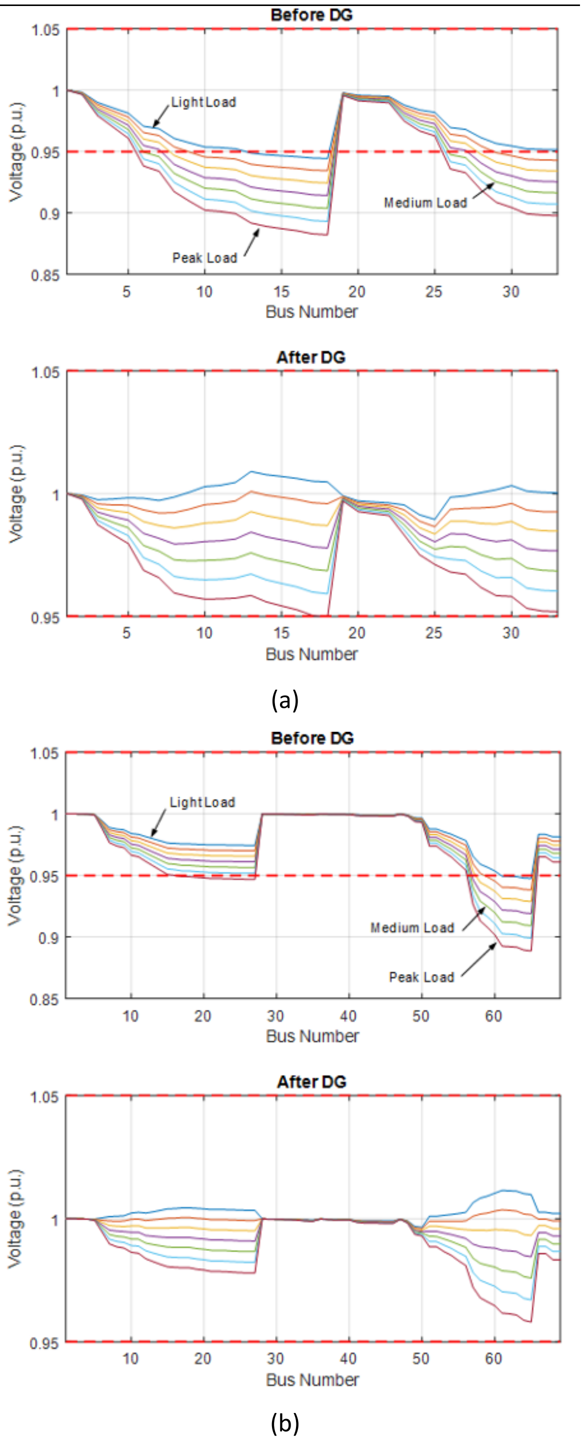
	449.00 (64)			
PSO-GSA [27]	400.00 (17) 1280.0 (61) 400.00 (65)	72.991	67.5521	0.9802
TLBO-GWO [26]	533.00 (18) 1000.00 (61) 773.00 (62)	71.74	68.1082	0.9791
PSO-WOA	455.60 (11) 342.90 (18) 1649.50 (61)	69.839	68.9530	0.9759

For IEEE 33-bus, the APLs obtained after installation of the same number of DG in different places for each algorithm are as follows: 89.200, 87.426, 87.280, 93.390, and 87.180 by the algorithms FPA, KHA, PSOIA, BSA-FES and WIPSO-GSA. As mentioned earlier, the result obtained by the proposed PSO-WOA is 87.165 kW. The results obtained by PSO-WOA so far are lower than those obtained by the compared algorithms.

In the case of IEEE 69-bus, the algorithms IWO, AGA, GATOPSIS, PSO-GSA, and HTLBO-GWO reduce the active losses to 74.590, 70.669, 73.59, 72.991 and 71.74 kW respectively. Since the APL obtained by the proposed algorithm is much better than the results obtained by the other algorithms, the PSO-WOA is evidently superior to the other algorithms in terms of minimization of APL.

The proposed algorithm was implemented in distribution systems to demonstrate its performance and effectiveness.

For all cases, the system feeder loads vary linearly from 60% (light load) to 120% (peak load) including a load step of 10 %. Moreover, the optimal sizing of DG is calculated by the hybrid PSO-WOA algorithm for each variation of load step. The voltage profile under various variations of loads for IEEE 33-bus, and 69-bus are shown in Figures 5.a, and 5.b respectively.



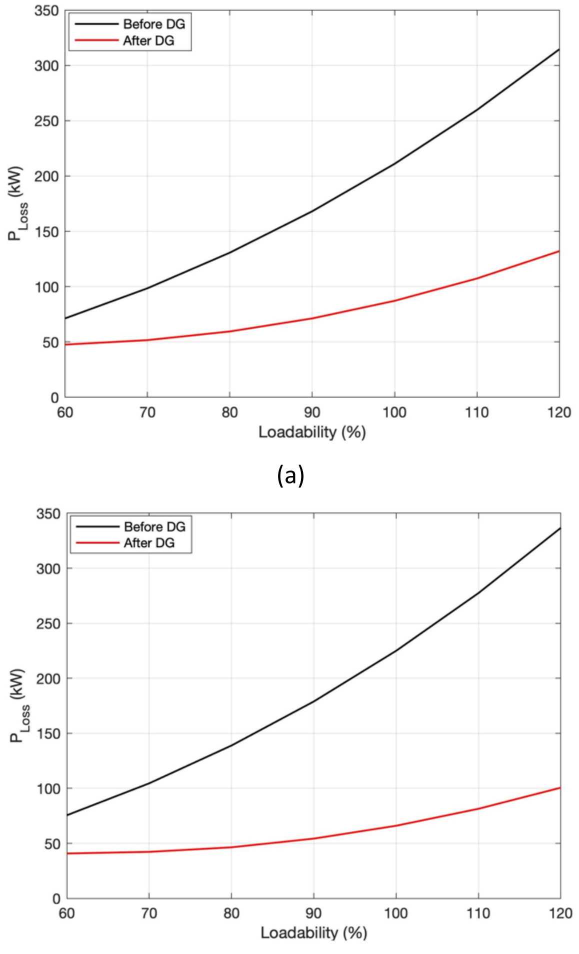
(a)

(b)

Figure 5: Voltage profile under different load variations. a). IEEE 33-bus, b). IEEE 69-bus.

From Figure 5, before the installation of DGs and with the linear variation of loads, the voltage value in some buses is under the specified limits (red dashed lines) such as all the buses from bus number 6 to 18 and from number 26 to 33. These buses are the weakest in IEEE 33-bus; the most vulnerable bus in this system is bus 18. After the installation of DGs, the bus voltage in the system improved.

The impact of loadability on total APLs before and after the integration of DG units for the studied test systems is illustrated in Figure 6. In the same manner, the loads varied linearly from 60% to 120% of consumption with a step of 10% and, simultaneously, the APL is calculated.



(a)

(b)

Figure 6: Total active power losses under different loadability values of test systems: a). IEEE 33-bus, b). IEEE 69-bus.

Analysis of Figure 6 shows that the variation in loads impacts the APL, i.e., the active losses increased or decreased proportionally with the increase or decrease in loads.

This remark would be valid for both studied systems, but the main observation is that the power losses decreased for all levels of loads after the integration of DGs.

Conclusions

In this paper, a hybrid PSO-WOA is proposed to find better allocation of Photovoltaic DG Units for two test systems: IEEE 33- and IEEE 69-bus. A multi-objective function was introduced to solve this problem, the APL index, TVV index and TOC were selected as functions for the objective function to minimize.

To validate the effectiveness of the hybrid PSO-WOA algorithm, the results obtained were compared with those of other recent algorithms, and the numerical results prove that the proposed algorithm outperforms the other algorithms.

Further, the ability of the algorithm to choose the appropriate placement and size was proved by the loadability study. The variation in loads shows that the selected locations and capacities of DGs are valid for different load levels and the DG always contributes to minimizing power losses for different consumption levels.

This work will be very informative for electric distribution companies seeking to incorporate small-sized renewable energy sources to EDS easily and reliably.

Nomenclature

A. Distribution system

DG	Distributed Generator
K_1	Coefficient of real power supplied cost, 4 $/kW
K_2	Costs of maintenance and installation, 5 $/kW
OF	Objective Function
APL	Active Power Loss
R_{ij}, X_{ij}	Resistance and reactance of line
TVV	Total Voltage Variation
V_i	Bus voltage
TOC	Total Operating Cost
V_{min}, V_{max}	Minimum and Maximum bus voltage value
ΔV_{max}	Maximum voltage drop
γ_1, γ_2, γ_3	Weighting factors
P_{Loss}	Total active loss on the EDS
P_{ij} , Q_{ij}	Active and reactive power in line
N_{bus}	Number of buses

B. DG Parameters

P_G, Q_G	Active and reactive power from sub-station
P_{DG}	Active power of DG
P_D, Q_D	Active and reactive power of load demand
S_{ij}	Apparent power in line
S_{max}	Maximum apparent power
P_{DG}^{min}	Minimum power injected by DG
P_{DG}^{max}	Maximum power injected by DG

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