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Analysis of Optimal Deployment of Several DGs in Distribution Networks Using Plant Propagation Algorithm

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ABSTRACT In recent years, the substantial upsurge of electricity demand has directly impacted the performance of the distribution networks concerning the active power losses and voltage drops. In such circumstances, the distributed generators (DGs) could uphold these concerns if they are optimally deployed in terms of sizing and placement. For this reason, in current research, the optimal deployment of DGs has been proposed with the plant propagation algorithm (PPA) to simultaneously maximize the total active power loss reduction and to upgrade the magnitude of the minimum bus voltage. Alongside, the authors have examined four rounds of DGs. In that context, the optimal deployment of one DG is investigated in the first round. In each succeeding round, the number of DGs is increased: in the second round, this investigation is carried out for two DGs, for three DGs in the third round, and finally, for four DGs in the fourth round of the investigation. The effectiveness of the proposed PPA has been tested on IEEE 33 and 69-bus test networks in the load flow analysis, and results are compared with the standard optimization algorithms. Thereafter, a post deployment economic assessment based on loss calculation has been undertaken out as well. The ANOVA test has also been performed for statistical evaluation of standard algorithms. The simulation results exhibit that the proposed algorithm outdo other algorithms both technically and economically. It has been seen that as the deployment of DGs is increased, the total active power losses and voltage drops are also reduced. In terms of economic assessments, the total cost decreases with the increased deployment of DGs in IEEE 33-bus test network, whereas, the total cost increases with the increased deployment of DGs in IEEE 69-bus test network.

INDEX TERMS Distributed generators, load flow analysis, sizing and placement of DGs, total active power losses, voltage drops, test networks, plant propagation algorithm (PPA).

NOMENCLATURE

AIS	Artificial immune system
ACO-ABC	Ant-colony-Artificial bee colony
ALO	Ant-lion optimizer
ANOVA	Analysis of variance
ASFLA	Adaptive shuffled frog leaping algorithm
BA	Bat algorithm
BFA	Bacterial foraging algorithm
CDE	Chaotic differential evolution
CSA	Chaotic sine cosine algorithm
CSFS	Chaotic stochastic fractal search
DG	Distributed generator
EMA	Exchange market algorithm
GA-GSA	Genetic-gravitational search techniques
GSA-GAMS	Gravitational search algorithm-general algebraic modelling system
GWO	Grey wolf optimizer
HA	Hybrid algorithm

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HGWO	Hybrid grey wolf optimizer
HSA	Harmony search method
MI	Maximum iterations
PPA	Plant propagation algorithm
PSAT	Power system analysis toolbox
QOCSOS	Quasi-oppositional chaotic symbiotic organisms search
SKHA	Stud krill herd algorithm
SPEA2	Strength pareto evolutionary algorithm 2
SSA	Salp swarm algorithm
TLCHS	Teaching learning combined with harmony search
WCA	Water cycle algorithm
WIPSO-GSA	Mixed weight improved particle swarm optimization-gravitational search
EHO	Elephant herding optimization
IHSA	Improved harmony search method

I. INTRODUCTION

In the last few decades, the load demand has grown extensively [1]. As a result, the overall line losses and voltage drops are also increased in the electrical networks. Given the fact that reactance to resistance ratio is comparatively low in the distribution networks than in the transmission networks, therefore, the line losses and voltage drops are more significant in the distribution networks [2]. One solution to boost the entire profile of the line losses and bus voltages leads to the reinforcement of distribution networks [3], [4]. However, it has turned out that only 20% of the reinforcement serves the peak load demand for only 5% of the total operating time [5]. Another solution leads to the incorporation of the DGs into the distribution systems. In recent years, the penetration level of DGs has a drastic growth due to their limited commissioning time [6], [7]. The integration of DGs outcome in an economical solution provided to their optimal deployment, as they can inject/absorb both active and reactive powers. In this way line losses and voltage drops could be minimized and the overall steadiness of the system increases [8], [9].

In the published literature, numerous authors have examined the deployment and allocation problem of DGs in IEEE 33 [10] and 69-bus distribution networks [11] to minimize the power losses and to improve the bus voltages. In [12], the authors have proposed ALO to size and locate one as well as two DGs. In [13], a PSAT based provision of one DG is presented. The authors in [14], have utilized ALO to optimally site PV based one and two DGs. In [15], the authors have implemented CSFS optimizer to find numbers, sizes, and sites of multiple DGs. In [16], a GWO is proposed for the allocation of one to two DGs to cater voltage stability and losses. The authors in [17], have introduced an EMA for the sizing and siting of both one and two DGs in the above-mentioned test networks. In [2], the optimal allocation of a DG is envisioned to accommodate the power flow, voltage stability, power factor, and line losses. In [18], the authors have employed the CDE optimizer for the DGs' placement. In [19], the authors have proposed a mixture of GA-GSA for a DG incorporation. In [20], a mixed WIPSO-GSA is proposed to install two DGs along with capacitors in the above-mentioned test networks.

In [21], the authors have proposed an HSA to scale three DGs in the test networks. In [22], a BFA has been proposed for the scaling of three DGs as well. The authors in [23], have presented a mixed ACO–ABC for the deployment of three DGs. Similarly, in [24], the authors have employed BA to scale PV systems' sizing in test networks. In [25], a HA to cater the power losses and voltage instability has been proposed with the deployment of three DGs. The HA uses an analytical variant of PSO. The authors in [26], have introduced an HGWO for the Indian networks to allocate three DGs. The authors in [27], have integrated three DGs in Portuguese 94-bus grid by using SKHA. In [17], the authors have exploited EMA for deploying three DGs in the considered networks. Analogously, the authors in [28], have applied SPEA2 to optimally integrate three DGs into the test networks. In [29], the authors have proposed the WCA to optimally size and site the three DGs in parallel to capacitors in the distribution systems. In [30], an SSA has been selected for locating the three DGs with capacitors in the distribution networks as well. In [31], an ASFLA for the optimal allocation of three DGs is selected. In [19], a combined GSA-GAMS has been availed for the optimal deployment of three DGs in the distribution networks. Similarly, the authors in [32], have tested the QOCSOS algorithm to search for the optimal locations of three DGs. In [33], a CSCA has been practiced for three DGs placement in the distribution networks. In [34], a combined TLCHS optimizer is tested to scale and site the four DGs in the distribution networks. The authors in [35], have utilized GA to optimally deploy one, two and three DGs into the IEEE 33-bus test network. In [36], the authors have presented an AIS to optimally deploy DGs in IEEE 33 and 15-node test systems. The authors in [37], have presented EHO to optimally size and place DGs in IEEE 15, 33 and 69-bus test networks. The authors in [38], have employed IHSA to size and site three DGs in IEEE 33-bus test networks.

A. RESEARCH GAP

From the above literature surveys, following observations could be observed:

- A large portion of authors have investigated the line loss and voltage drop problem by the optimal deployment of DGs in the IEEE 33 and 69-bus distribution networks. Some of the authors have investigated the deployment of one DG, a few authors have investigated the deployment of two DGs and some authors have investigated the deployment of both one and two DGs in the test networks. Most of the authors have investigated the deployment of three DGs in the test networks. The deployment of four DGs has been seen to be very rare.

- Besides, the deployment of several DGs in multiple rounds has been seen to be lacking in a single paper in the same test networks as well.
- Apart from that, the post deployment economic assessment based on loss calculation is also seen to be undiscovered.
- In the context of solution algorithms, the standard algorithms like ALO, CSFS, GWO, EMA, GA, OCDE, GA-GSA, LSF, ACO-ABC, BA, HA, HGWO, SPEA2, SSA, GSA-GAMS, QOCSOS, CSCA, TLCHS and CDE have been used to get the optimal solution. The application of PPA has been seen to be uncharted for optimal deployment of DGs in the distribution networks.
- The statistical analysis of the algorithms using standard methods like ANOVA has also been seen to be rare in the existing literature.

B. MAIN CONTRIBUTIONS

In current paper, the authors propose following contributions:

- The line loss and voltage drop problem in IEEE 33 and 69-bus test networks has been investigated in multiple rounds such that in the first round the optimal deployment of a one DG is investigated, in the second round the optimal deployment of two DGs is investigated, in the third round the optimal deployment of three DGs is investigated and in the fourth round the optimal deployment of four DGs is investigated. The objective function is to simultaneously maximize the total active power loss reduction and to upgrade the magnitude of the minimum bus voltage.
- A post deployment economic assessment based on loss calculation has been undertaken as well in all of the four rounds. The economic assessment exhibits the impact of increasing the number of DGs on the total cost. The total cost comprises of the investment cost of DGs, operational cost of the network and cost of losses.
- A new algorithm known as PPA [39] is proposed to search the optimal sizing and placement of DGs in the load flow analysis. Earlier, the PPA has been applied to certain problems in the power systems like optimal demand response programs [40]–[44], economic dispatch [45], automatic generation control [46] and optimal DGs' integration [47]. As per the authors' best of knowledge, the PPA has been an uncharted algorithm in the optimal sizing and placement problem of DGs in test networks in multiple rounds. PPA is multi-path algorithm inspired by the propagation of the strawberry plant. The algorithm possesses both characteristics like exploration and exploitation. Exploration describes the wide expansion over a search space, whereas, exploitation corresponds to finding of best local solutions. It is the reason which increases the diversity of the algorithm.
- The statistical analysis using Big-O and ANOVA has been done for different algorithms.

The rest of the paper is ordered as follows. In part II, the working methodology is explained. It includes load flow analysis, PPA algorithm and method of economic assessment. In part III, the mathematical modeling of the optimization problem has been carried out. In part IV, the results and analysis has been presented. The part V concludes the paper.

II. METHODOLOGY

In this part, the utilized methodology has been presented. The methodology includes a load flow analysis in which the optimal sizes and places of the DGs have been searched by the PPA. When the termination criteria is met, an economic assessment based on loss calculation has been done.

A. LOAD FLOW ANALYSIS

The load flow analysis outcomes the magnitudes of the active and reactive powers, and the voltages and angles at all buses of energy network. These parameters are then used to compute the power losses and bus voltage drops. Newton Raphson's load flow (NRLF) is the most widely used load flow method in the literature [48]. NRLF analysis follows a sequential approximation appertaining to an initial presume of the variables. By virtue of its quadratic convergence, the NRLF analysis is less likely to diverge with malevolent issues as well [49]. For any network, the voltage at p^{th} bus could be calculated as shown Eq. (1) [50].

$$\underline{v}_p = \frac{1}{\underline{Y}_{pp}}\left[\frac{(P_p - jQ_p)}{\underline{v}_p^*} - \sum_{\substack{p=1 \\ p\neq i}}^{NB} \underline{Y}_{pi}\underline{v}_i\right] \tag{1}$$

where, $\underline{v}_p$ denotes the phasor voltage at the p^{th} bus. P_p and Q_p represent the magnitudes of active and reactive powers at the p^{th} bus respectively. $\underline{v}_p^*$ denotes the conjugate of the phasor voltage at the p^{th} bus. $\underline{Y}_{pp}$ depicts the phasor Y-bus matrix at the p^{th} bus and $\underline{Y}_{pi}$ depicts the phasor Y-bus matrix between p^{th} and i^{th} buses. $\underline{v}_i$ denotes the phasor voltage at the i^{th} bus. NB corresponds to total buses. P_p and Q_p could be calculated as shown in Eq. (2) and Eq. (3).

$$P_p = \sum_{i=1}^{NB} Y_{pi}v_i v_p \cos(\theta_{pi} + \delta_i - \delta_p) \tag{2}$$

$$Q_p = -\sum_{i=1}^{NB} Y_{pi}v_i v_p \sin(\theta_{pi} + \delta_i - \delta_p) \tag{3}$$

where, Y_{pi} is the magnitude of admittance between p^{th} and i^{th} buses. v_i and v_p point out the voltage magnitudes at i^{th} and p^{th} buses respectively. θ_{pi} corresponds to the angle of Y_{pi}. δ_i and δ_p are the voltage angles corresponding to v_i and v_p respectively. The line current between two buses shall be determined as shown in Eq. (4).

$$\underline{I}_{pi} = \frac{\underline{v}_p - \underline{v}_i}{\underline{Z}_{pi}} \tag{4}$$

where, $\underline{I}_{pi}$ is the current phasor between p^{th} and i^{th} buses. $\underline{v}_p$ and $\underline{v}_i$ denote the phasor voltages at p^{th} and i^{th} buses respectively. $\underline{Z}_{pi}$ denotes the phasor impedance between p^{th} and

i^{th} buses. The apparent powers at p^{th} and i^{th} buses shall be calculated as shown in Eq. (5) and Eq. (6).

$$\underline{S}_p = \underline{v}_p \underline{I}_{pi}^* = P_p + jQ_p \tag{5}$$
$$\underline{S}_i = \underline{v}_i \underline{I}_{pi}^* = P_i + jQ_i \tag{6}$$

where, $\underline{S}_p$ and $\underline{S}_i$ represent the complex apparent powers at p^{th} and i^{th} buses respectively. Similarly, $\underline{v}_p$ and $\underline{v}_i$ represent the phasor voltages at p^{th} and i^{th} buses respectively. $\underline{I}_{pi}^*$ denotes the conjugate of phasor current between p^{th} and i^{th} buses. P_p, P_i, Q_p and Q_i correspond to the magnitudes of the active and reactive powers at p^{th} and i^{th} buses respectively. j denotes the complex entity with value is $\sqrt{} - 1$. The active power loss (line loss) shall be calculated as shown in Eq. (7).

$$P_{LOSS\_pi} = P_p - P_i \tag{7}$$

where, P_{LOSS_pi} represents the line loss between p^{th} and i^{th} buses.

B. PLANT PROPAGATION ALGORITHM

The PPA was developed by F. Merrikh-Bayat [51] in 2014. This algorithm is inspired by the propagation of the strawberry plant. Each mother plant grows roots and runners in search of water and minerals. The runner is a daughter plant, which after adequate growth separates from the mother plant and acts as a new mother plant. In each iteration, each mother plant originates a runner and a root within its vicinity. Afterwards, the fitness is computed at the localities based on the referral by the roots and the runners. Half of the best locations are selected as mother plants for the next iteration and rest are discarded. The iterations are repeated till the MI are reached.

Mathematically, PPA could be defined in three stages, namely initialization, duplication and elimination. In the initialization stage, the number of mother plants (N_m) and respective lengths of roots (l_{root}) and runners (l_{runner}) are defined. If z is the objective function to be minimized/maximized, the locality of the h^{th} mother plant at the q^{th} iteration is found in the duplication stage. The matrices saving the localities of the respective roots and runners at the q^{th} iteration are shown in Eq. (8) and Eq. (9) [45]. The resultant matrix saving the localities of respective roots and runners is shown in Eq. (10).

$$Z_{root}\left(q\right) = \left[Z_{1,root}(q), Z_{2,root}(q) \ldots Z_{Nm,root}(q)\right] \tag{8}$$
$$Z_{runner}\left(q\right) = \left[Z_{1,runner}(q), Z_{2,runner}(q) \ldots Z_{Nm,runner}(q)\right] \tag{9}$$
$$Z_{prop}(q) = \left[Z_{root}\left(q\right) Z_{runner}\left(q\right)\right] \tag{10}$$

where, $Z_{root}\left(q\right)$ constitutes the matrix saving the localities of randomly originated roots $Z_{1,root}\left(q\right)$ etc. Similarly, $Z_{runner}\left(q\right)$ constitutes the matrix saving the localities of randomly originated runners $Z_{1,runner}\left(q\right)$ etc. At any instant the resultant matrix $Z_{prop}\left(q\right)$ saves the results of matrices $Z_{root}\left(q\right)$ and $Z_{runner}\left(q\right)$.

In the elimination stage, the fitness of the roots and runners is calculated as shown in Eq. (11).

$$\begin{aligned} &fitness\left(z_{h,prop}\left(q\right)\right) \\ &= \{\frac{1}{f\left(z_{h,prop}(q)\right)}, \quad f\left(z_{h,prop}(q)\right) > 0 \\ &= \{\frac{1}{\left|f\left(z_{h,prop}(q)\right)\right|}, \quad f\left(z_{h,prop}(q)\right) \leq 0 \end{aligned} \tag{11}$$

where, $f(\cdot)$ is the fitness of the objective function. After the fitness value is computed, the probability p_h of selecting the h^{th} parameter could be calculated as shown in Eq. (12).

$$p_h = \frac{fitness\left(z_{h,prop}\left(q\right)\right)}{\sum_{g=1}^{N} fitness\left(z_{g,prop}\left(q\right)\right)} \tag{12}$$

In current problem, the mother plants represent DGs' size and location, and lengths of roots and runners determine the fitness of the DGs' size and location. The stepwise procedure of PPA search steps are as follows:

Step I: In this step, the initialization stage is completed. The PPA parameters for initial population like number of mother plants and respective lengths of roots and runners, and number of iterations are defined.

Step II: In this step, the duplication stage is completed. The mother plants with respective roots and runners are randomly originated.

Step III: In this step, the fitness of the randomly originated mother plants is evaluated. This fitness is based on the lengths of the roots and runners from the mother plant. Those random solutions which have short lengths of the runners from the mother plants are more fit as compared to others. Therefore, half of these solutions are contested in the next iteration with the newly originated population.

Step IV: In this step, the elimination stage is completed. The fitness of the randomly originated mother plants is evaluated after each iteration. At the end of the MI, mother plant (along with respective roots and runners) with highest probability is selected as optimal solution.

The flowchart of the PPA is shown in Fig. 1. In terms of DGs' sizing and placement, the PPA search steps are as follows:

Step 1: Perform the load flow analysis based on given data of slack, PV and PQ buses without adding any DGs. Evaluate the objectives.

Step 2: Initialize the PPA parameters in terms of DGs' sizing and placement. Originate an initial population of DGs' sizes and locations. Simultaneously originate two additional random numbers, the distance of which determines the lengths of the roots and runners from the DG's size and location.

Step 3: Compute the fitness of the DGs' sizes and locations using Eq. (11), and again perform the load flow analysis based on the fitness values. Select half of the best results and save the data. Evaluate the objectives.

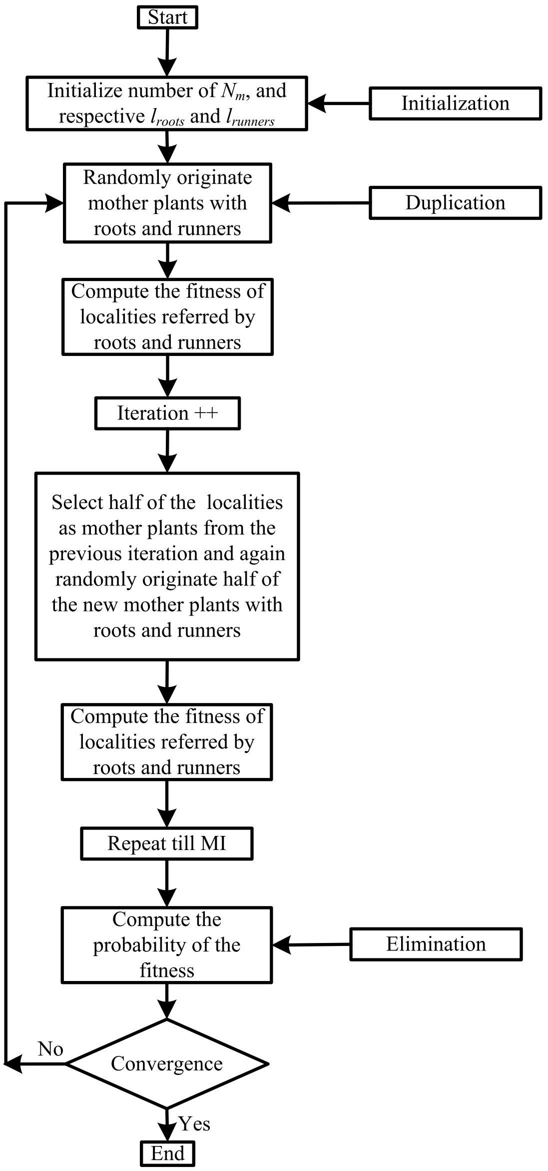

FIGURE 1. Demonstration of the flowchart of the PPA for realizing it in terms of DGs' sizing and placement.

Step 4: Again, originate the random mother plants with respective roots and runners. Compute the fitness while considering the half of the mother plants from previous iteration as well. Perform the load flow analysis based on fitness values. Select half of the best results and save the data. Evaluate the objectives.

Step 5: Repeat step 3 and step 4 till MI.

Step 6: Compute the probability of fitness using Eq. (12) and save the data.

C. METHOD OF ECONOMIC ASSESSMENT

The method of economic assessment determines that if the placement of DGs is profitable or not. The placement will only be profitable if the total cost (which is the sum of the investment cost of DGs and the operational cost) with DGs will be much lesser than the cost without DGs. The input power from the main grid to the electrical network is consumed by the total load and losses. If DGs are located at certain buses in the electrical network, this power could be calculated as shown in Eq. (13).

$$P_{IN} = P_{LOSS} + \sum P_{LOAD} - \sum P_{DG} \tag{13}$$

where, P_{IN} denotes the power fed from the main grid, P_{LOSS} represents the total active power loss in the network, $\sum P_{LOAD}$ corresponds to total load and $\sum P_{DG}$ corresponds to total power injection of DGs. All these powers are measured in kW. For a period of one year (8760h), the input energy E_{IN} could be calculated as shown in Eq. (14).

$$E_{IN} = P_{IN}.8760h \tag{14}$$

E_{IN} is measured in kWh. For a certain electricity tariff G_T, the cost of input energy could be calculated as shown in Eq. (15).

$$K_{EIN} = E_{IN} G_T \tag{15}$$

where, K_{EIN} is the annual cost of input energy and is measured in \$. G_T is measured in \$/kWh. The annual cost of energy occurs at the end of the year and, therefore, it has to be accumulated to present value by using the capital recovery factor β as shown in Eq. (16). β is calculated as shown in Eq. (17) [52].

$$K_{AE} = K_{EIN}.\beta \tag{16}$$

$$\beta = \frac{(1 + I_F)}{(1 + I_R)} \tag{17}$$

where, K_{AE} corresponds to the accumulated cost of input energy at time zero. I_F denotes the inflation rate and I_R denotes the interest rate. The total cost aggregates the sum of the investment cost of DGs plus the accumulated cost of energy and it could be calculated as shown in Eq. (18).

$$K_{GE} = K_{PR} \sum P_{DG} + K_{AE} \tag{18}$$

where, K_{GE} is the total cost in \$. Similarly, K_{PR} is the investment cost of the DGs and is measured in \$/kW. The percentage cost reduction could be calculated as shown in Eq. (19).

$$K_{GE}(\%) = \left(\frac{K_{GE\_WITHOUTDGs} - K_{GE\_WITHDGs}}{K_{GE\_WITHOUTDGs}} \right)(100) \tag{19}$$

where, $K_{GE\_WITHOUTDGs}$ is the total cost in \$ without DGs and $K_{GE\_WITHDGs}$ is the total cost in \$ with the DGs.

III. MODELLING OF THE OPTIZATION PROBLEM

In this part, the mathematical modeling of the optimization problem has been carried out. The objective function is to simultaneously maximize the reduction of the total active power loss and to upgrade the magnitude of the minimum bus voltage in the test networks.

Mathematically, the maximization of the reduction of the total power loss is shown in Eq. (20) and Eq. (21).

$$FO_1 = \max P_{LOSS} \tag{20}$$

$$P_{LOSS} = \frac{\left(P_{LOSS\_WITHOUTDGs} - P_{LOSS\_WITHDGs}\right)}{P_{LOSS\_WITHOUTDGs}} \quad (21)$$

where, FO_1 corresponds to first objective, P_{LOSS} denotes the reduction of total active power loss, $P_{LOSS\_WITHOUTDGs}$ aggregates the total power loss without the DGs and $P_{LOSS\_WITHDGs}$ aggregates the total power loss with the DGs. P_{LOSS} could be represented in percentage as well, as shown in Eq. (22). This representation will be used for comparison purpose with other standard algorithms.

$$P_{LOSS}\,(\%) = \frac{\left(P_{LOSS\_WITHOUTDGs} - P_{LOSS\_WITHDGs}\right)}{P_{LOSS\_WITHOUTDGs}} (100) \quad (22)$$

Similarly, the upgradation of the magnitude of the minimum bus voltage is shown in Eq. (23).

$$FO_2 = max\ v_p \quad (23)$$

where, FO_2 corresponds to second objective, v_p denotes the magnitude of voltage at the p^{th} bus and it shall be calculated by using Eq. (1). Both objectives could be converted to a single objective function after a normalized weighted addition. Value of P_{LOSS} is already normalized, whereas, for the normalization of minimum bus voltage, it is divided by the standard voltage of 1 (p.u). The single objective function (FO) is calculated by using Eq. (24).

$$FO = W_1 FO_1 + W_2 FO_2 \quad (24)$$

where, W_1 and W_2 correspond to weights and have value of 0.5 each. The objectives are subject to certain constraints as mentioned below. The total power fed from the main grid and the DGs should be equal to total load and losses as shown in Eq. (25).

$$P_{IN} + \sum P_{DG} = \sum P_{LOAD} + P_{LOSS} \quad (25)$$

where, P_{IN} denotes the power fed from the main grid, $\sum P_{DG}$ corresponds to total power injection of DGs, $\sum P_{LOAD}$ corresponds to total load and P_{LOSS} represents the total active power loss. The magnitude of bus voltages should retain within boundaries as shown in Eq. (26).

$$v_{pl} \leq v_p \leq v_{pu} \quad (26)$$

where, v_{pl} is the lower boundary and v_{pu} is the upper boundary of the voltage at the p^{th} bus. Similarly, the magnitude of the line currents must be retained within upper boundary as shown in Eq. (27).

$$I_l < I_{lu} \quad (27)$$

where, I_l is the line current in the l^{th} line and I_{lu} corresponds to its upper limit. The active power supplied by the DGs should be within upper and lower boundaries as shown in Eq. (28).

$$0 < \sum P_{DG} \leq \sum P_{LOAD} \quad (28)$$

where, $\sum P_{LOAD}$ holds as the upper boundary.

IV. RESULTS

In this part, the simulation results and their analysis has been exhibited. The load flow analysis has been carried out on test networks. IEEE 33-bus distribution network is designated as test network 1, whereas IEEE 69-bus distribution network is designated as test network 2 [53]. The optimal sizes and places of the DGs have been searched using the PPA, such that to maximize the reduction of the total active power loss and to upgrade the magnitude of the minimum bus voltage. The complete system has been modelled and simulated in MATLAB environment and has been run for 20 times. Four rounds have been investigated in each of the test networks, as follows:

1. In the round 1, the objective function has been analyzed with the deployment of a one DG in the test networks using PPA in the load flow analysis.
2. In the round 2, the objective function has been analyzed with the deployment of a two DGs in the test networks using PPA in the load flow analysis.
3. In the round 3, the objective function has been analyzed with the deployment of a three DGs in the test networks using PPA in the load flow analysis.
4. In the round 4, the objective function has been analyzed with the deployment of a four DGs in the test networks using PPA in the load flow analysis.

The results of the four rounds in each test network have been matched with the standard algorithms. In the end, a comparison among the four rounds has been done as well. Table 1 displays the simulation parameters.

TABLE 1. Simulation parameters.

Parameters	Test Network 1	Test Network 2
Initial Population (PPA)	30	30
MI (PPA)	30	30
Range of DGs' Sizes (kW)	10~4000	10~4000
K_{PR} ($/kW) [28]	350	350
G_T ($/kWh) [52]	0.19	0.19
I_R (%) [28]	12.5	12.5
I_F (%) [28]	9	9
No of Runs	20	20

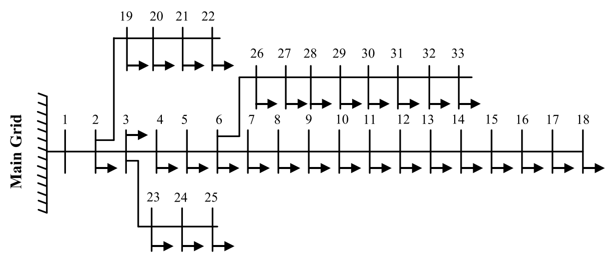

FIGURE 2. Test Network 1.

A. TEST NETWORK 1

The IEEE 33-bus test network [8] is displayed in Fig. 2. The network consists of 37 lines connected to 33 buses. The total

TABLE 2. Results with one DG (Round 1-Network 1).

Algorithm Ref.	Year	v_{min} (p.u)	*FO*	P_{LOSS} (kW)	P_{LOSS} (%)	K_{GE} (S)	DG's Size (kW)	DG's Location
ALO [12]	2017	0.9503	0.7309	101.82	51.15	3049439.423	2450	6
LSF [13]	2017	N/A	0.22285	115.54	44.57	4007223.193	1700	29
ALO [14]	2018	0.9424	0.70805	109.70	47.37	2887084.408	2590.2	6
CSFS3 [15]	2018	N/A	0.2369	109.68	47.38	2887300.666	2590	6
GWO [16]	2019	N/A	0.2405	108.18	48.1	2870303.047	2601.7	6
EMA [17]	2018	0.9510	0.719	106.93	48.70	2961641.884	2526.9	6
GA [2]	2019	0.9425	0.7082	109.66	47.39	2874789.12	2600	6
OCDE [18]	2019	0.9423	0.70815	109.64	47.4	2897466.21	2581.8	6
GA-GSA [19]	2019	0.9433	0.7093	109.37	47.53	2887400.022	2589.52	6
GA [35]	2019	0.970	0.71	114.64	45	2525859.759	2886	7
AIS [36]	2019	0.934	0.724	101.30	51.4	3360552.051	2200	7
EHO [37]	2019	0.927	0.6655	124.23	40.4	4215138.788	1544.5	30
Proposed PPA	**2020**	**0.960**	**0.7615**	91.09	**56.3**	**1547375.942**	**3640**	**6**
Without DGs	--	0.929	--	208.45	--	6276971.732	--	--

active load of this network is 3720kW and reactive load is 2300kVAR. The load flow analysis of this network results in a total active power loss of 208.4592kW and a minimum voltage magnitude of 0.929 (p.u).

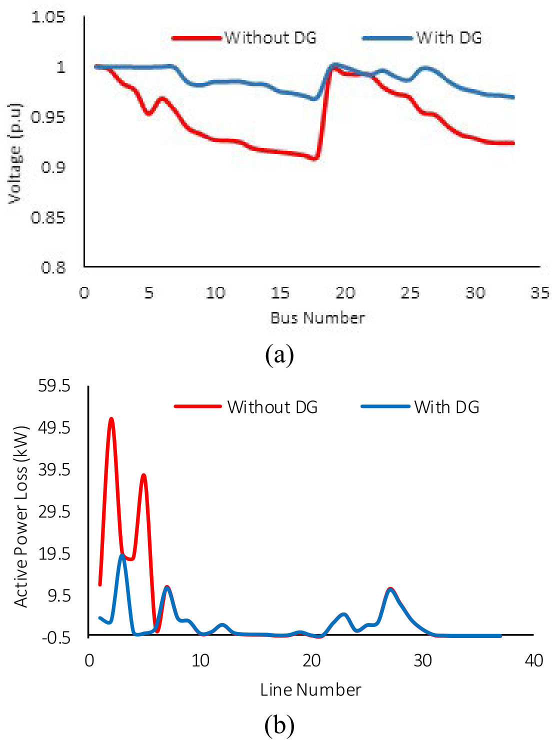

FIGURE 3. (a) Improved voltage profile with one DG's deployment in round 1-Network 1, (b) Improved active power loss profile with one DG's deployment in round 1-Network 1.

1) ROUND 1 (NETWORK 1)

In this round, a one DG (which supplies active power) has been optimally sized and placed at different buses with the proposed PPA in the load flow analysis. After the analysis, the value of objective function is found to be 0.7615. Whereas, the total active power loss has been curtailed to 91.09kW. In percentage it corresponds a loss reduction of 56.3%. Similarly, the magnitude of the minimum bus voltage has been upgraded to 0.960 (p.u). Fig. 3 (a) displays the complete voltage profile and Fig. 3 (b) displays the complete active power loss profile of round 1 (with and without DG). Table 2 shows the comparison of the results of the proposed PPA with the standard algorithms for the round 1. It can be seen that with the proposed PPA, the percentage reduction of the total active power loss and the magnitude of the bus voltages have been significantly improved. Likewise, it can be noticed that with the proposed PPA, the minimum cost of $1547375.942 has been reached, which shows a percentage cost reduction of 75.35%.

2) ROUND 2 (NETWORK 1)

In this round, two DGs (which supply active power) have been optimally sized and placed at different buses with the proposed PPA in the load flow analysis. After the analysis, the value of objective function is found to be 0.840. Whereas, the total active power loss has been curtailed to 64.11kW. In percentage it corresponds a loss reduction of 69.24%. Similarly, the magnitude of the minimum bus voltage has been upgraded to 0.970 (p.u). Fig. 4 (a) displays the complete voltage profile and Fig. 4 (b) displays the complete active power loss profile of round 2 (with and without DGs). Table 3 shows the comparison of the results of the proposed PPA with the standard algorithms for the round 2. It can be seen that with the proposed PPA, the percentage reduction of the total active power loss and the magnitude of the bus voltages have been significantly improved. Likewise, it can be noticed that with the proposed PPA, the minimum cost of $1646529.085 has been reached, which shows a percentage cost reduction of 73.76%.

3) ROUND 3 (NETWORK 1)

In this round, three DGs (which supply active power) have been optimally sized and placed at different buses with the proposed PPA in the load flow analysis. After the analysis, the value of objective function is found to be 0.8445. Whereas, the total active power loss has been curtailed to 58.41kW. In percentage it corresponds a loss reduction of 71.9%. Similarly, the magnitude of the minimum bus voltage has been upgraded to 0.970 (p.u). Fig. 5 (a) displays the complete voltage profile and Fig. 5 (b) displays

TABLE 3. Results with two DGs (Round 2-Network 1).

Algorithm Ref	Year	v_{min}	*FO*	P_{LOSS} (kW)	P_{LOSS} (%)	K_{GE} (S)	DGs' Size (kW)	DGs' Location
ALO [12]	2017	0.9732	0.79085	81.60	60.85	3527367.214	850, 1191.1	13, 30
ALO [14]	2018	0.9688	0.7778	86.13	58.68	3574525.123	851.5, 1157.6	13, 30
GWO [16]	2019	N/A	0.2925	86.50	58.5	3565104.616	856.9, 1160.23	13, 30
EMA [17]	2018	0.9631	0.76955	88.38	57.6	3817879.144	816.38, 1000.58	11, 33
GA-GSA [13]	2019	0.9684	0.7783	85.83	58.82	3574657.786	851.05, 1157.57	13, 30
CSFS3 [15]	2018	N/A	0.29345	86.11	58.69	3573368.775	852, 1158	13, 30
WPISO-GSA [20]	2018	N/A	0.2912	87.04	58.24	3599824.054	850, 1140	13, 30
GA [35]	2019	0.981	0.7855	85.46	59	3556107.367	844, 1179	13, 30
Proposed PPA	**2020**	**0.970**	**0.840**	64.11	**69.24**	**1646529.085**	**1271, 2255**	**3, 6**
Without DGs	--	0.929	--	208.45	--	6276971.732	--	--

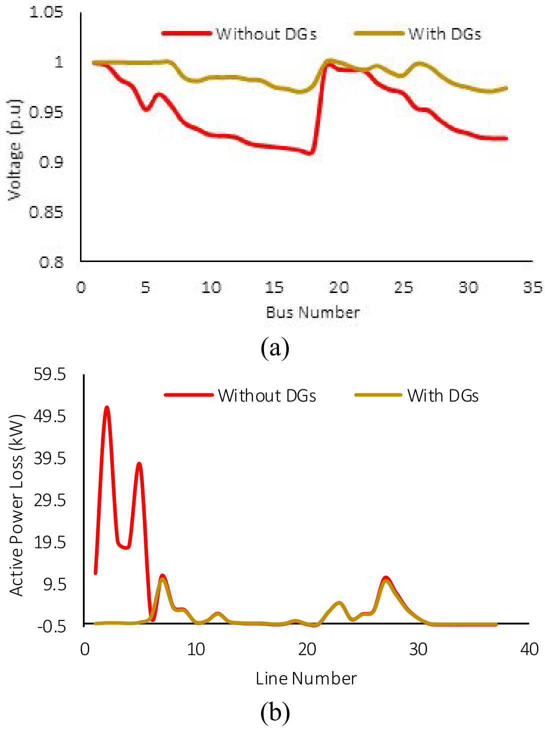

FIGURE 4. **(a) Improved voltage profile with two DGs' deployment in round 2-Network 1, (b) Improved active power loss profile with two DGs' deployment in round 2-Network 1.**

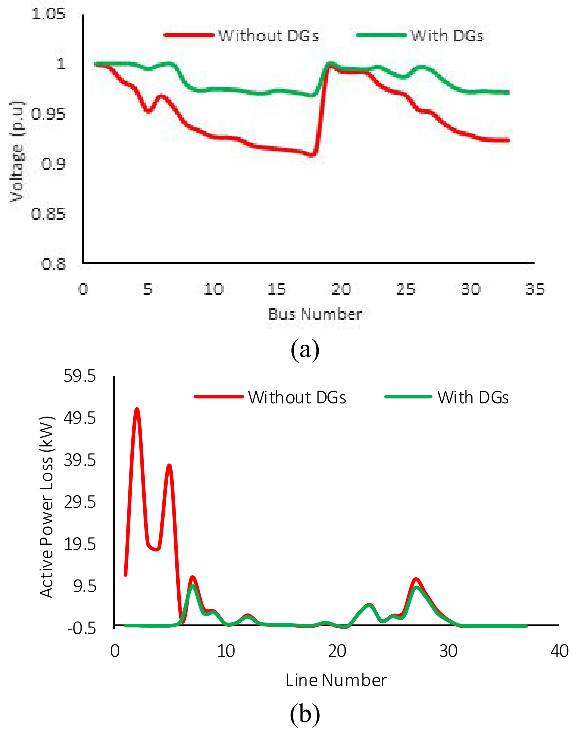

FIGURE 5. **(a) Improved voltage profile with three DGs' deployment in round 3-Network 1, (b) Improved active power loss profile with three DGs' deployment in round 3-Network 1.**

the complete active power loss profile of the round 3 (with and without DGs). Table 4 shows the comparison of the results of the proposed PPA with the standard algorithms for the round 3. It can be seen that with the proposed PPA, the percentage reduction of the total active power loss and the magnitude of the bus voltages have been significantly improved. Except than BA [24], where the minimum voltage has a slight improvement with a magnitude of 0.98. Likewise, it can be noticed that with the proposed PPA, the minimum cost of $1647632.005 has been reached, which shows a percentage cost reduction of 73.75%.

4) ROUND 4 (NETWORK 1)

In this round, four DGs (which supply active power) have been optimally sized and placed at different buses with the proposed PPA in the load flow analysis. After the analysis, the value of objective function is found to be 0.849. Whereas, the total active power loss has been curtailed to 58.366kW. In percentage it corresponds a loss reduction of 72%. Similarly, the magnitude of the minimum bus voltage has been upgraded to 0.979 (p.u). Fig. 6 (a) displays the complete voltage profile and Fig. 6 (b) displays the complete active power loss profile of the round 4 (with and without DGs). Table 5 shows the comparison of the results of the proposed PPA with the standard algorithms for the round 4. It can be seen that with the proposed PPA, the percentage reduction of the total active power loss and the magnitude of the bus voltages have been significantly improved. Likewise, it can be noticed that with the proposed PPA, the minimum cost of $1662916.844 has been reached, which shows a percentage cost reduction of 73.50%.

Fig. 7 shows the convergence curve of objective function using the PPA for the test network 1 in all of the four rounds. It can be seen that for round 1, the objective function converges in 16 iterations, while for round 2 in 16.8 iterations,

TABLE 4. Results with three DGs (Round 3-Network 1).

Algorithm Ref.	Year	v_{min}	FO	P_{LOSS} (kW)	P_{LOSS} (%)	K_{GE} (S)	DGs' Size (kW)	DGs' Location
ACO-ABC [23]	2015	0.9735	0.80075	77.54	62.8	2416673	754.7, 1099.9, 1071.4	14, 24, 30
BA [24]	2016	0.98	0.805	77.12	63	2671810.7	816.3, 952.35, 952.35	15, 25, 30
HA [25]	2016	N/A	0.3205	74.83	64.1	2482221.2	790, 1070, 1010	13, 24, 30
HGWO [26]	2017	N/A	0.322	74.20	64.4	2386387.4	802, 1090, 1054	13, 24, 30
EMA [17]	2018	0.9684	0.8058	74.37	64.32	3335752.5	976.6, 1169.09, 943.54	30, 24, 12
SPEA2 [28]	2018	0.9616	0.8363	60.24	71.1	2207928	691, 733.4, 742.9	18, 29, 8
SSA [30]	2019	0.9686	0.8083	73.37	64.8	2411758.6	753.6, 1100.4, 1070.6	13, 23, 29
GSA-GAMS [19]	2019	0.9686	0.8125	71.62	65.64	2382120.1	801.22, 1091.3, 1053.59	13, 24, 30
GA [35]	2019	0.986	0.828	68.78	67		761, 1170, 1082	14, 24, 30
QOCSOS [32]	2020	N/A	0.3275	71.91	65.5	2422802.8	801.7, 1091.3, 1053.6	13, 24, 30
CSCA [33]	2020	0.969	0.807	73.99	64.5	2381975	871, 1091.47, 954.08	13, 24, 30
IHSA [38]	2020	N/A	0.326	72.54	65.2	2393205.391	800.8, 1087.6, 1050,7	13, 24, 30
Proposed PPA	**2020**	**0.970**	**0.8445**	**58.41**	**71.9**	**1647632.005**	**1141.8, 161.71, 2214.3**	**13, 23, 28**
Without DGs	--	0.929	--	208.45		6276971.732	--	--

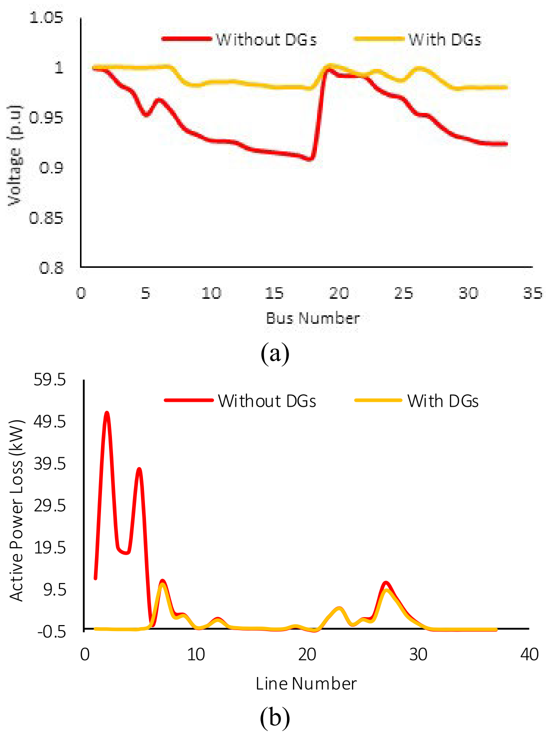

FIGURE 6. (a) Improved voltage profile with four DGs' deployment in round 4-Network 1, (b) Improved active power loss profile with four DGs' deployment in round 4-Network 1.

for round 3 in 18 iterations and for round 4 in 20 iterations. It reflects the robustness of the proposed PPA.

B. TEST NETWORK 2

The IEEE 69-bus test network [9] is displayed in Fig. 8. The network consists of 37 lines connected to 33 buses. The total active load of this network is 3802kW and reactive load is 2696kVAR. The load flow analysis of this network results in a total active power loss of 225.007kW and a minimum voltage magnitude of 0.9091 (p.u).

1) ROUND 1 (NETWORK 2)

In this round, a one DG (which supplies active power) has been optimally sized and placed at different buses with the proposed PPA in the load flow analysis. After the analysis, the value of objective function is found to be 0.829. Whereas, the total active power loss has been curtailed to 68.7885kW. In percentage it corresponds a loss reduction of 67%. Similarly, the magnitude of the minimum bus voltage has been upgraded to 0.97105 (p.u). Fig. 9 (a) displays the complete voltage profile and Fig. 9 (b) displays the complete active power loss profile of round 1 (with and without DG). Table 6 shows the comparison of the results of the proposed PPA with the standard algorithms for the round 1. It can be seen that with the proposed PPA, the percentage reduction of the total active power loss and the magnitude of the bus voltages have been significantly improved. Except than GA [2], where the percentage reduction of total active power loss is moderately improved than PPA with a value of 72%. Likewise, it can be noticed that with the proposed PPA, the minimum cost of $3448360.684 has been reached, which shows a percentage cost reduction of 46.4%.

2) ROUND 2 (NETWORK 2)

In this round, two DGs (which supply active power) have been optimally sized and placed at different buses with the proposed PPA in the load flow analysis. After the analysis, the value of objective function is found to be 0.843. Whereas, the total active power loss has been curtailed to 64.11kW.

TABLE 5. Results with four DGs (Round 4-Network 1).

Algorithm Ref	Year	v_{min}	*FO*	P_{LOSS} (kW)	P_{LOSS} (%)	K_{GE} (S)	DGs' Size (kW)	DGs' Location
TLCHS [34]	2018	0.977	0.8271	67.28	67.72	1929856.446	941.2, 684.7, 966.4, 710.7	6, 14, 24, 31
CDE [18]	2019	0.9702	0.8241	67.12	67.8	2033171.863	926.69, 646.7, 967.3, 679.3	6, 14, 24, 31
Proposed PPA	**2020**	**0.979**	**0.8495**	**58.36**	**72**	**1662916.844**	**1058, 2201, 171.7, 74.80**	**3, 6, 4, 5**
Without DGs	--	0.929	--	208.45		6276971.732	--	--

TABLE 6. Results with one DG (Round 1-Network 2).

Algorithm Ref.	Year	v_{min} (p.u)	*FO*	P_{LOSS} (kW)	P_{LOSS} (%)	K_{GE} (S)	DG's Size (kW)	DG's Location
ALO [12]	2017	0.9679	0.802	81.801	63.645	3818908.374	1800	61
ALO [14]	2018	0.9682	0.799	83.25	63	3730339.848	1872.7	61
EMA [17]	2018	0.9689	0.800	82.87	63.17	3682855.453	1910.3	57
GA [2]	2019	0.9682	0.844	63.00	72	3728689.476	1850	60
CSFS3 [15]	2018	N/A	0.315	83.23	63.01	3729932.194	1873	61
CDE [18]	2019	0.9683	0.799	83.25	63	3730714.195	1872.4	61
Proposed PPA	**2020**	**0.97105**	**0.829**	**74.25**	**67**	**3448360.684**	**2088**	**57**
Without DGs	--	0.9091		225.007	--	6434437.248	--	--

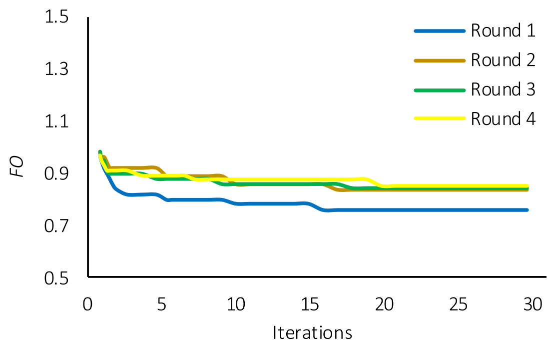

FIGURE 7. Convergence curves for test network 1 in four rounds using PPA.

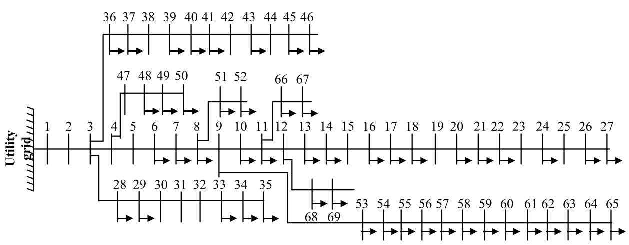

FIGURE 8. Test Network 2.

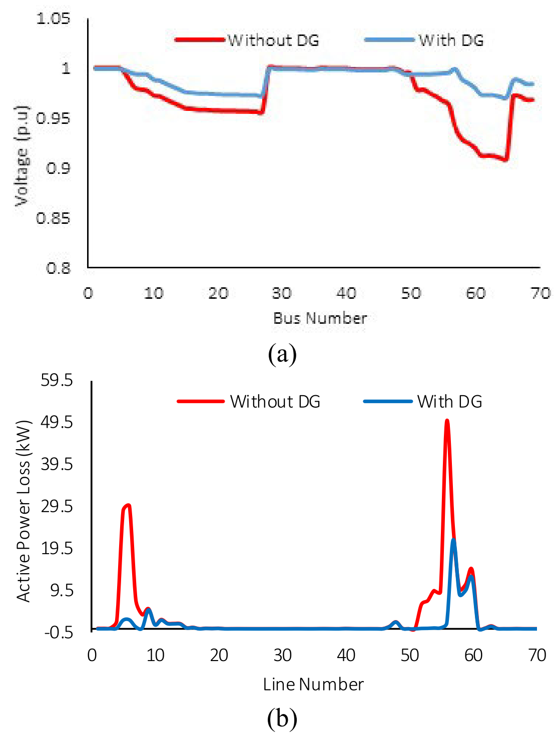

FIGURE 9. (a) Improved voltage profile with one DG's deployment in round 1-Network 2, (b) Improved active power loss profile with one DG's deployment in round 1-Network 2.

In percentage it corresponds a loss reduction of 69.24%. Similarly, the magnitude of the minimum bus voltage has been upgraded to 0.971 (p.u). Fig. 10 (a) displays the complete voltage profile and Fig. 10 (b) displays the complete active power loss profile of round 2 (with and without DGs). Table 7 shows the comparison of the results of the proposed PPA with the standard algorithms for the round 2. It can be seen that with the proposed PPA, the percentage reduction of the total active power loss and the magnitude of the bus voltages have been significantly improved. Except than ALO [12], where the minimum voltage has a slight improvement with a magnitude of 0.980. Likewise, it can be noticed that with the proposed PPA, the minimum cost of $2432658.205 has been reached, which shows a percentage cost reduction of 61.19%.

3) ROUND 3 (NETWORK 2)

In this round, three DGs (which supply active power) have been optimally sized and placed at different buses with the

TABLE 7. Results with two DGs (Round 2-Network 2).

Algorithm Ref.	Year	v_{min} (p.u)	FO	P_{LOSS} (kW)	P_{LOSS} (%)	K_{GE} (S)	DG's Size (kW)	DG's Location
ALO [12]	2017	0.9801	0.832	70.77	68.547	3255161.07	538.7, 1700	17,61
ALO [14]	2018	0.9789	0.830	71.68	68.14	3163828.284	531.48, 1781.5	17,61
EMA [17]	2018	0.9794	0.830	71.86	68.06	2885555.463	1886.9, 649.3	61, 69
CSFS3 [15]	2018	N/A	0.340	71.68	68.14	3165051.151	531, 1781	17, 61
Proposed PPA	**2020**	**0.97105**	**0.835**	**69.11**	**69.24**	**2432658.205**	**1040, 1856**	**7, 57**
Without DGs	--	0.9091		225.007	--	6434437.248	--	--

TABLE 8. Results with three DGs (Round 2-Network 3).

Algorithm Ref.	Year	v_{min} (p.u)	FO	P_{LOSS} (kW)	P_{LOSS} (%)	K_{GE} (S)	DG's Size (kW)	DG's Location
HSA [21]	2013	0.967	0.7905	86.85	61.4	4000932	1302.4, 369, 101.8	63, 64, 65
BFOA [22]	2014	0.9808	0.8232	75.24	66.56	3589441	295.4, 447.6, 1345.1	27, 65, 61
HGWO [26]	2017	0.98	0.8357	69.43	69.14	2909086	527,380, 1718	11, 17, 61
WCA [29]	2018	0.987	0.8345	71.55	68.2	3295547	775, 1105, 438	61, 62, 23
SSA [30]	2019	0.9789	0.83495	69.52	69.1	2909230	380,527, 1718	17, 10, 60
FWA [31]	2019	0.974	0.81395	77.87	65.39	3822249	480.5, 1198.6, 225.8	65, 61, 27
SFLA [31]	2019	0.9752	0.81475	77.784	65.43	3408950	1088.7, 167.3, 980.9	57, 63, 26
QOCSOS [32]	2020	NA	0.3457	69.43	69.14	2908712	526.8, 380.4, 1719.0	11, 18, 61
CSCA [33]	2020	0.98	0.834	70.20	68.8	3557580	365.9, 1675.85, 65.52	17, 61, 67
Proposed PPA	**2020**	**0.982**	**0.905**	**40.50**	**82**	**2770049.7**	**27.919, 1108.3, 1558.3**	**51, 61, 62**
Without DGs	--	0.9091		225.007	--	6434437.248	--	--

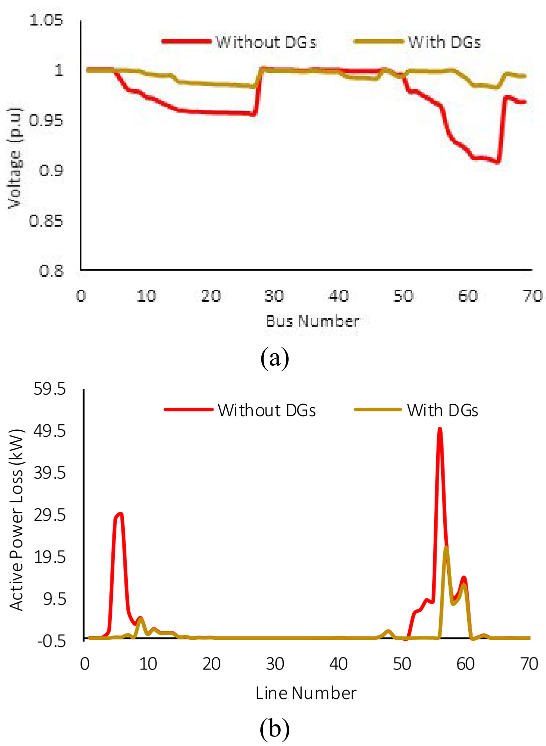

FIGURE 10. (a) Improved voltage profile with two DGs' deployment in round 2-Network 2, (b) Improved active power loss profile with two DGs' deployment in round 2-Network 2.

proposed PPA in the load flow analysis. After the analysis, the value of objective function is found to be 0.906. Whereas, the total active power loss has been curtailed to 36.00kW. In percentage it corresponds a loss reduction of 82%. Similarly, the magnitude of the minimum bus voltage has been upgraded to 0.982 (p.u). Fig. 10 (a) displays the complete voltage profile and Fig. 10 (b) displays the complete active power loss profile of the round 3 (with and without DGs). Table 8 shows the comparison of the results of the proposed PPA with the standard algorithms for the round 3. It can be seen that with the proposed PPA, the percentage reduction of the total active power loss and the magnitude of the bus voltages have been significantly improved. Likewise, it can be noticed that with the proposed PPA, the minimum cost of $2770049.7 has been reached, which shows a percentage cost reduction of 56.94%.

4) ROUND 4 (NETWORK 2)

In this round, four DGs (which supply active power) have been optimally sized and placed at different buses with the proposed PPA in the load flow analysis. After the analysis, the value of objective function is found to be 0.958. Whereas, the total active power loss has been curtailed to 15.96kW. In percentage it corresponds a loss reduction of 92.3415%. Similarly, the magnitude of the minimum bus voltage has been upgraded to0.97829 (p.u). Fig. 11 (a) displays the complete voltage profile and Fig. 11 (b) displays the complete active power loss profile of the round 4 (with and without DGs). Table 9 shows the comparison of the results of the proposed PPA with the standard algorithms for the round 4. It can be seen that with the proposed PPA, the percentage

TABLE 9. Results with four DGs (Round 4-Network 2).

Algorithm Ref.	Year	v_{min} (p.u)	*FO*	P_{LOSS} (kW)	P_{LOSS} (%)	K_{GE} (S)	DG's Size (kW)	DG's Location
PSO	2020	0.97827	0.948	18.40	91.8204	2437136.517	1002, 100.14, 115, 1615	7, 57, 58, 61
Proposed PPA	**2020**	**0.97829**	**0.950**	17.23	**92.3415**	**2484839.695**	**1014, 47.22, 145, 1586.3**	**7, 57, 58, 61**
Without DGs	--	0.9091		225.007	--	6434437.248	--	--

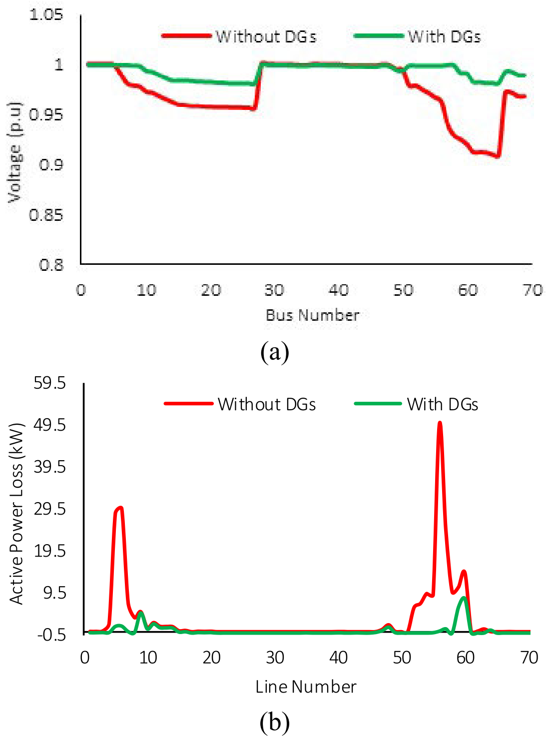

FIGURE 11. (a) Improved voltage profile with three DGs' deployment in round 2-Network 3, (b) Improved active power loss profile with three DGs' deployment in round 2-Network 3.

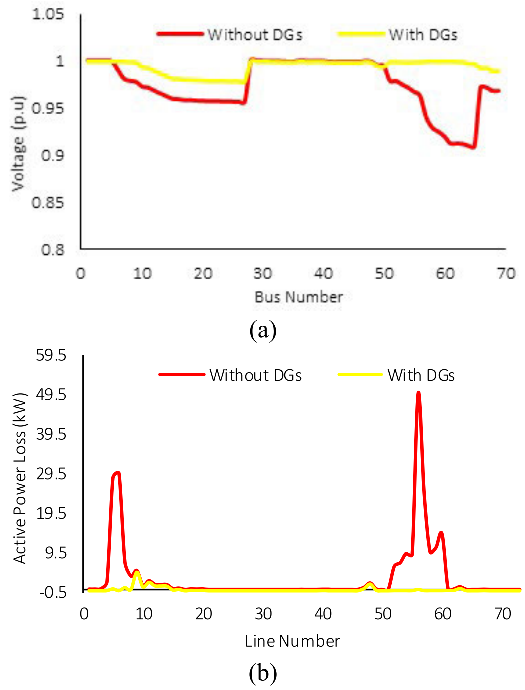

FIGURE 12. (a) Improved voltage profile with four DGs' deployment in round 4-Network 2, (b) Improved active power loss profile with four DGs' deployment in round 4-Network 2.

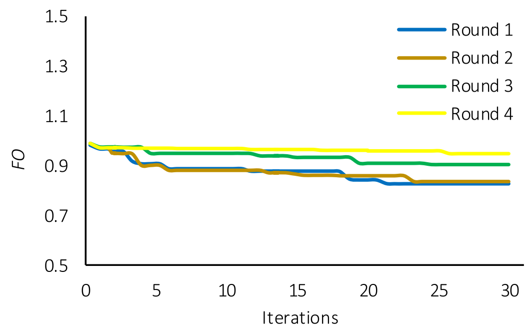

FIGURE 13. Convergence curves for test Network 2 in four rounds using PPA.

reduction of the total active power loss and the magnitude of the bus voltages have been significantly improved. Likewise, it can be noticed that with the proposed PPA, the minimum cost of \$2484839.695 has been reached, which shows a percentage cost reduction of 61.38%.

Fig. 13 shows the convergence curve of objective function using PPA for the test network 2 in all of the four rounds. It can be seen that for round 1, the objective function converges in 21 iterations, while for round 2 in 23 iterations, while for round 3 in 25 iterations and for round 4 in 26 iterations. It reflects the robustness of the proposed PPA.

C. COMPARISON OF ROUNDS

In this part, the comparison among the four rounds has been carried out for both of the test networks based on results of proposed PPA in the load flow analysis. The comparison takes into account the four major parameters including the objective function, reductions in total active power loss, magnitudes of the minimum bus voltage and the total cost.

Table. 10 shows the comparison among the four rounds in test network 1. It can be noticed that as percentage reduction in total active power loss is maximized along with the upgradation of the magnitude of the minimum bus voltage, the total cost increases along with objective function. It means that injection of more DG power results in increased costs, however the objectives are best met as well. It can be

TABLE 10. Comparison of rounds in test Network 1.

Round	*FO*	v_{min} (p.u)	P_{LOSS} (kW)	P_{LOSS} (%)	K_{GE} (S)	K_{GE} (%)
Round 1	0.7615	0.960	91.09	56.3	1547375.942	75.35
Round 2	0.840	0.970	64.11	69.24	1646529.085	73.76
Round 3	0.8445	0.970	58.41	71.9	1647632.005	73.75
Round 4	0.8495	0.979	58.366	72	1662916.844	73.50

TABLE 11. Comparison of rounds in test Network 2.

Round	*FO*	v_{min}	P_{LOSS} (kW)	P_{LOSS} (%)	K_{GE} (S)	K_{GE} (%)
Round 1	0.829	0.97105	68.7885	67	3448360.684	46.4
Round 2	0.835	0.97105	64.11	69.24	2432658.205	61.19
Round 3	0.905	0.982	36.00	82	2770049.7	56.94
Round 4	0.950	0.97829	15.96	92.3415	2484839.695	61.38

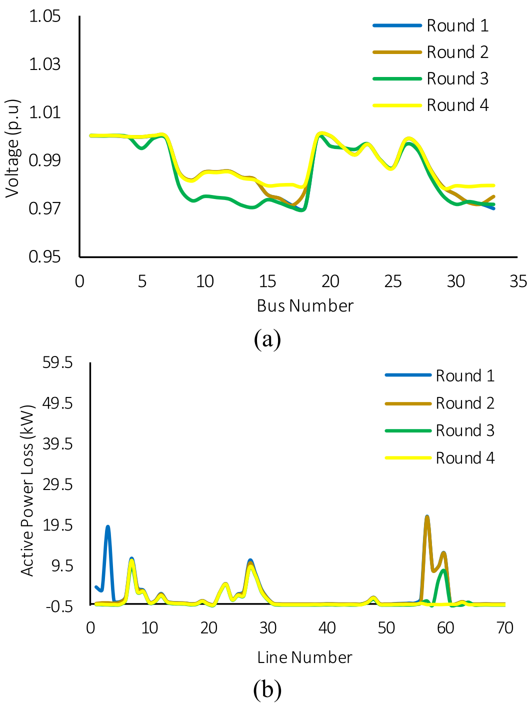

FIGURE 14. Comparison of (a) Voltage profiles and (b) Active power loss profiles in test Network 1.

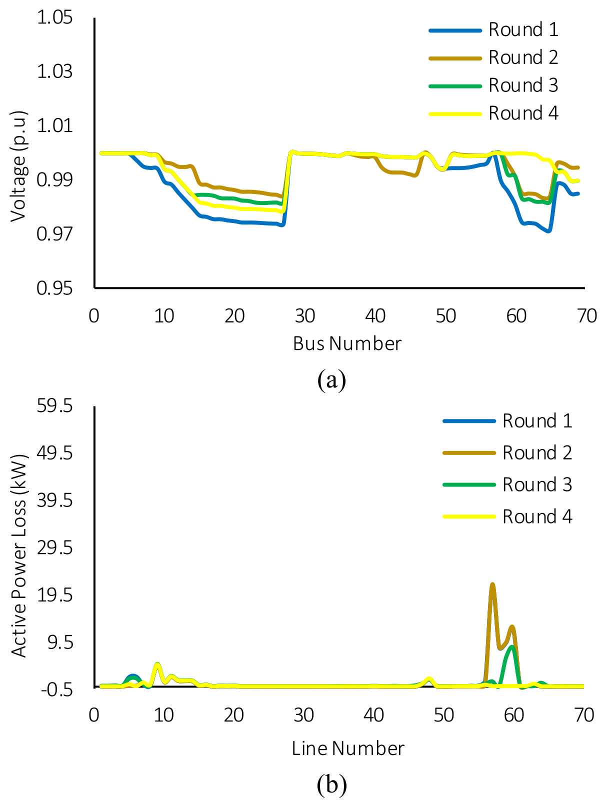

FIGURE 15. Comparison of (a) Voltage profiles and (b) Active power loss profiles in test Network 2.

further noticed from Table 10 that for the rounds 2, 3 and 4, the magnitudes of the minimum bus voltage are approximately at par. On the other hand, a drastic rise in the percentage reduction in total active power loss is present. In addition, Fig. 14 (a) displays the voltage profiles achieved among the four rounds. It is evident that round 4 has the best voltage profile. Round 3 has the worst voltage profile, whereas the rounds 1 and 2 have almost the same profile. In addition to that, Fig. 14 (b) displays the active power loss profiles achieved among the four rounds. It can be seen that round 4 has the best active power loss profile, whereas, the round 2 has the worst profile. On the other hand, round 3 is better than round 1 for active power loss profile.

Likewise, Table. 11 shows the comparison among the four rounds in test network 2. It can be noticed again that as the percentage reduction in total active power loss is maximized along with the upgradation of the magnitude of the minimum bus voltage, the total cost increases along with objective function as well. It means that injection of more DG power results in increased costs, however the objectives are best met as well. It can be further noticed from Table 11 that for the rounds 1 and 2, the magnitudes of the minimum bus voltage are at par. On the other hand, a slight rise in the percentage reduction in total active power loss is present. Further, for the rounds 3 and 4, the magnitudes of the minimum bus voltage are nearly at par. Conversely, an ample rise in the percentage reduction in total active power loss is present. Additionally, Fig. 15 (a) displays the voltage profiles achieved among the four rounds. It is evident that round 2 has the best voltage profile. Round 1 has the worst voltage profile, whereas the rounds 3 and 4 have almost the same profile. Besides, Fig. 15 (b) displays the active power loss profiles achieved among the four rounds. It can be seen that round 4 has the best active power loss profile, whereas, the round 2 has the worst profile. On the other hand, round 1 is better than round 3 for total active power loss profile.

TABLE 12. Statistical analysis of PPA after 20 runs.

Rounds	OF	Best	Worst	Mean
Test Network 1				
Round 1	v_{min} (p.u)	0.9656	0.9554	0.96
	P_{LOSS}	0.583	0.543	0.563
Round 2	v_{min} (p.u)	0.9734	0.96999	0.97
	P_{LOSS}	0.6954	0.6904	0.6924
Round 3	v_{min} (p.u)	0.987	0.968	0.97
	P_{LOSS}	0.739	0.6999	0.719
Round 4	v_{min} (p.u)	0.987	0.968	0.979
	P_{LOSS}	0.79	0.66	0.72
Test Network 2				
Rounds	***OF***	**Best**	**Worst**	**Mean**
Round 1	v_{min} (p.u)	0.98105	0.96105	0.97105
	P_{LOSS}	0.69	0.655	0.67
Round 2	v_{min} (p.u)	0.99105	0.95105	0.97105
	P_{LOSS}	0.745	0.64	0.6924
Round 3	v_{min} (p.u)	0.98	0.984	0.982
	P_{LOSS}	0.85	0.79	0.82
Round 4	v_{min} (p.u)	0.99829	0.95829	0.97829
	P_{LOSS}	0.9534	0.903	0.9234

D. STATISTICAL ANALYSIS

In this part, the statistical analysis of the objective function obtained by using the PPA has been carried out. The algorithm has been run for 20 times in the load flow analysis for each of the test network and results from the Big-O analysis are tabulated in Table 12 [54]. It can be seen that the variation of the objective function between the upper and lower bounds obtained by the PPA is not very much. It reflects the robustness of the proposed algorithm.

Similarly, Table 13 shows the results of the ANOVA test. ANOVA tests helps to find out the variance of the objective function with different algorithms [55]. For test network 1, the ANOVA test has been carried out between seven algorithms. Whereas, for test network 2, the test has been performed between five algorithms. Table 8 shows that the calculated value of F for both test networks is less than the tabulated value at 5% significance level. It means that the calculated F-Ratio for both test networks is greater than the standard values at 5% significance level. It shows that the variation obtained while calculating the objection function is significant and not by chance [56].

TABLE 13. ANOVA test.

Source of Variation	Sum of Square	Degrees of Freedom	Mean Square	F-Ratio	5% F-Limit [57]
Test Network 1					
Between Groups	0.680	6	0.113	5.295	3.865
Within Groups	0.150	7	0.021		
Test Network 2					
Between Groups	0.3894	4	0.097	267.6	5.192
Within Groups	0.0018	5	0.0003		

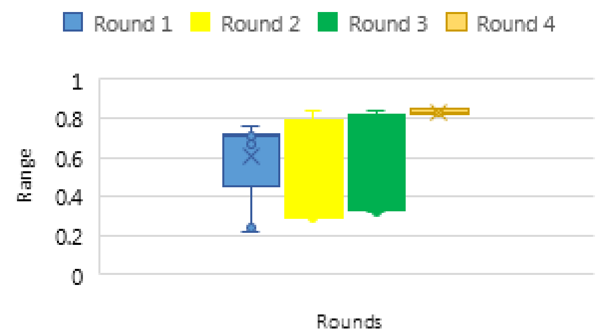

FIGURE 16. Box plot for comparison of objective function among four rounds in test Network 1.

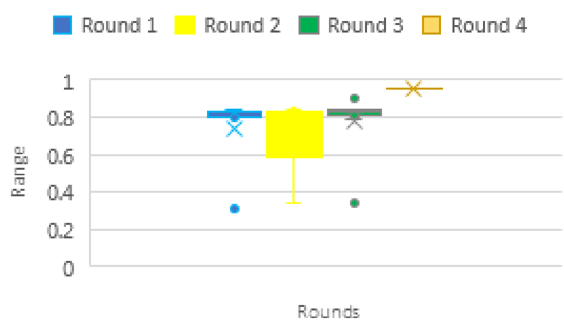

FIGURE 17. Box plot for comparison of objective function among four rounds in test Network 2.

Likewise, Fig. 16 and Fig. 17 show the box plots for both of the test networks in four rounds respectively. It is evident that there are no outliers and data is significant for statistical analysis.

V. CONCLUSION

In current paper, the total active power loss and voltage drop problem in test networks is investigated with the optimal deployment of several DGs using the PPA in the load flow analysis. Four rounds of DGs were examined in two test networks such that in the first round the optimal deployment of a one DG is investigated, in the second round the optimal deployment of two DGs is investigated, in the third round the optimal deployment of three DGs is investigated and in the fourth round the optimal deployment of four DGs is investigated. The objectives were to simultaneously maximize the reduction of the total power loss and to upgrade the magnitude of the minimum bus voltage. Thereafter, a post deployment economic assessment based on loss calculation has been undertaken as well. Following conclusions could be deduced:

- With the proposed PPA, the overall results have been bettered as compared to standard algorithms in all of the four rounds in both of the test networks. However, certain algorithms like BA in round 3 network 1 has shown a slight improvement in magnitude of minimum bus voltage. Similarly, GA in round 1 network 2 has shown a moderate improvement in percentage reduction of total active power loss. ALO in round 2 network 2 has shown a slight improvement in magnitude of minimum bus voltage.
- From the comparison among the four rounds in both test networks, round 4 where maximum deployment of DGs was undertaken, gives the best result in terms of objective function. The increased deployment of DGs have a significant impact on the maximization of the percentage reduction in active power loss than the upgradation of minimum bus voltage.
- The increased deployment of DGs in all of the four rounds in test network 1 has resulted in reduction of total costs.
- The increased deployment of DGs in all of the four rounds in test network 2 has resulted in increase of total costs.
- The ANOVA test proves that the variation obtained while calculating the objection function is significant and not by chance.
- The box plots show that there are no outliers and data is significant for statistical analysis.

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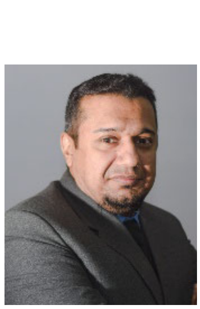

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