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Advanced Optimization Algorithm-based Method for Enhancing the Power Quality of the Distribution Networks with Photovoltaic Units

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Abstract—*These Recent studies focused on the importance of the installation of renewable distributed generations like photovoltaic (PV) in the distribution system. The enhancement of voltage profile, power quality, and power loss reduction are the major significations of photovoltaic integration. Optimization methods of the salp swarm algorithm (SSA), and marine predictor algorithm (MPA) have been employed for the optimal allocation of photovoltaic units in the distributed systems. This paper is divided into two stages: the first stage incorporates the loss sensitivity factor (LSF) to determine the most candidate buses for RDG integration, and the second stage determines the optimal location, within the candidate buses selected in the first stage, and the capacity of RDGs. The capacity of RDGs is calculated based on the maximum load of each bus. The optimal location is calculated based on the load and the capacity of each bus. The optimal location of each RDG is determined by using thesalp swarm algorithm (SSA), and the marine predictor algorithm (MPA). The algorithm is tested using 33 bus routes. The results show that the proposed algorithm is efficient in terms of time and computational cost. Moreover, an inclusive comparison among the suggested optimization methods has been conducted for selecting the best solutions for RDGs units' allocation. The proposed techniques have been tested on one network, IEEE 33 nodes radial distribution network (RDN) in MATLAB, and the achievements are compared with other algorithms for more validation of the proposed methodologies.*

Keywords— photovoltaic; renewable distributed generations; Optimization algorithms; power quality

1. INTRODUCTION

In the last decades, Distributed generations (DGs) integration into distribution systems performs a remarkable role in distribution network planning due to their numerous technical, environmental, and economic benefits [1, 2]. DG is considered a small power plant connected to the grid or installed near customers. This technology consists of three types of renewable DG (wind, PV, fuel cells, biomass, etc.), non-renewable DG (internal combustion engines, etc.), and a hybrid of both. More research is focused on the integration of RDGs into the radial distribution system especially PV and WT systems to produce cleaner energy because of their availability in nature [3, 4].

Recently, there are several optimization techniques that have been successfully utilized to tackle RDGs allocation problems and their sizes. The optimization algorithms are divided into three types, analytical techniques, meta-heuristic techniques, and hybrid optimization techniques [5]. Analytical techniques are iterative–analytical technique [6], an analytical technique [7], and an efficient analytical(EA) technique [1]. However, most of the attempts failed to identify the optimal sizing and placement of multiple RDGs, which motivated researchers to search for more effective methodologies [8]. In this case, meta-heuristic optimization techniques introduced themselves as an auspicious solution that can conquer the complexities associated with the optimal allocation of RDGs and attain high-quality outcomes.

Accordingly, the optimization problems is solved by meta-heuristic algorithms and the most popular meta-heuristic techniques are [9], artificial bee colony method (ABC) [10], Manta Ray Foraging optimization algorithm (MRFO) [11], Transient Search Optimization (TSO) [12], honey bee mating optimization (HBMO) [13], Equilibrium optimization (EO) [14], Quasi-Oppositional Chaotic Symbiotic Organisms Search (QOCSOS) [15], particle swarm optimization (PSO) [15], Sine Cosine Algorithm (SCA) [16], whale optimization algorithm (WOA) [17, 18], Tunicate Swarm Algorithm (TSA) [19], harmony search (HS) [20, 21], modified crow search (MCS) [22], adaptive cuckoo search (ACS) [23], Adaptive Shuffled Frogs Leaping Algorithm (ASFLA) [24], fireworks algorithm (FA) [25], coyote algorithm [26], uniform voltage distribution algorithm (UVD) [27], biogeography-based optimization (BBO) [28], hyper cube ant colony optimization(HCACO) [29], modified plant growth simulation (MPGS) [30], grey wolf optimizer (GWO) [31], and salp swarm algorithm (SSA) [32]. Hybrid methodologies were developed to overcome the problems of analytical and meta-heuristic techniques. As an example of hybrid methods is the joined execution of both the Grasshopper Optimization Algorithm (GOA) and Cuckoo Search (CS) [33], multi-objective hybrid teaching–learning-based optimization–grey wolf optimizer (MOHTLBOGWO) [34], improved PSO and gravitational search algorithm (WIPSO–GSA) [35], hybrid genetic particle swarm optimization [40], and hybrid PSOGSA optimization algorithm [36].

In this work, the suggested methodologies have been performed on various distribution networks like 33-bus, and 69-bus for optimal location in RDN using the forward–backward sweep (BFS) load flow algorithm. The BFS algorithm is applied in RDN due to its high speed and accuracy, flexibility, and superior in convergence [37, 38].
The proposed SSA, GWO, IGWO, MPA, and SOA techniques have been simulated as Injects real power only from DG (DG Type-I PV Units).
Additionally, the loss sensitivity factor (LSF) is incorporated to select which node has the most loss reduction when a DG is integrated. In addition, the optimal allocation of RDGs in distribution network and its size are estimated by applying the suggested techniques. Further, the obtained simulation results have been comprehensively compared with other techniques and the simulation is performed using MATLAB package.

2. MATHEDOLOGY

2.1 Computational of power flow issue

The major purpose of the current paper is to identify the best places and capacities of the RDGs in radial networks that decrease the system losses dependent on several constraints. The summation of the power imported from the infinite bus and the total generation of renewable sources in the network under study must equal the load consumption and the power losses in the distribution feeders. Fig. 1 presents the single line scheme of a radial distribution system, presenting a line n_{mr} is constructed between two bus-bars "r" and "m".

The Backward/Forward Sweep (BFS) methodology is used to address the load flow problems of radial distributors [50] that might be subdivided into three stages:(i) Backward Sweep, (ii) Forward Sweep, and (iii) nodal current analysis. The convergence of these phases will be occurred when the maximum mismatch between voltages is lower than the epsilon tolerance (ε_t) that equal 0.00001, when the convergence is reached, the reactive / active power losses of the RDN can be simply identified. The calculations of BFS power flow are employed in the following points:

estimated by (i) backward sweep direction by the formula presented in (1).

$$P_{r,m} = P'_m + R_{r,m}\frac{\left(P'^2_m + Q'^2_m\right)}{V^2_m} \tag{1}$$

$$Q_{r,m} = Q'_m + X_{r,m}\frac{\left(P'^2_m + Q'^2_m\right)}{V^2_m} \tag{2}$$

where $P'_m = P_m + P_{Lm}$ and $Q'_m = Q_m + Q_{Lm}$, P_{Lm} and Q_{lm} are the active and reactive power consumed by load connected to buss "m".

The voltage amplitude and its angle at each bus can be estimated with respect to (ii) the step of forward sweep, while the $V_r\angle\delta_r$ symbolizes the voltage at node 'r' and $V_m\angle\delta_m$ represents the voltage at node 'm'.

The according to (iii) the node current flowing via the line that has an impedance, $Z_{rm} = R_{rm} + jX_{rm}$ and is located within bus "r" and bus "m" can be estimated by:

$$I_{r,m} = \frac{(V_r\angle\delta r - V_m\angle\delta m)}{R_{r,m} + jX_{r,m}} \tag{3}$$

$$I_{r,m} = \frac{(P_r - jQ_r)}{V_r\angle - \delta r} \tag{4}$$

The voltage at node "m" can be estimated as follow,

$$V_m = [V^2_r - 2\left(P_r R_{r,m} + jQ_r X_{r,m}\right) + \left(R^2_{r,m} + X^2_{r,m}\right).\frac{\left(P^2_r + jQ^2_r\right)}{V^2_r}]^{\frac{1}{2}} \tag{5}$$

where P_r and Q_r are the active and reactive power flow via the transmission branch located between nodes r and m, respectively.

$R_{r,m}$ and $X_{r,m}$ denotes to the resistance and reactance of the line section installed between nodes "r" and "m". V_r and V_m are the voltage of nodes "r" and "m", respectively.

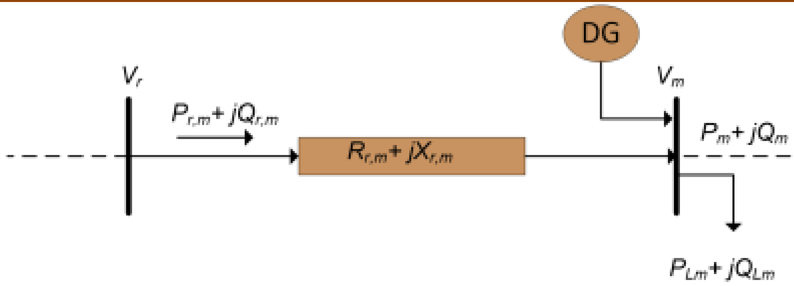

Fig. 1 Single line representation of distribution network.

2.2 Objective function

In the current work, the objective function for the optimal RDGs allocation problem is incorporated as multi objective function for reducing the total losses, voltage deviations, and net operating cost of the RDS and at the same time enhancing the voltage shape and improving the stability index. The objective function (OF) is evaluated by the following equation:

$$\min(\mathrm{OF}) = \lambda_1\, \Delta\mathrm{P}_{\mathrm{l,DG}} + \lambda_2\, \Delta\mathrm{V}_{\mathrm{Dev}} + \lambda_3\, \Delta\mathrm{OC} \tag{18}$$

$$\lambda_{\mathrm{f}} = \sum_{\mathrm{k}=1}^{3} \lambda_{\mathrm{k}} = 1.0 \qquad \text{range } (0-1) \tag{19}$$

where, λ_f indicates the weight factors of the OF [27].

3. Optimiazation methods

3.1 Marine Predators Algorithm (MPA)

The MPA methodology has been discussed in [54]. In this algorithm, the predator and victim are treated as search agents because the victim is also trying to obtain its nutrition jointly when a predator is searching for its victim [55]. The flowchart of the MPA has been shown in Fig. 2.

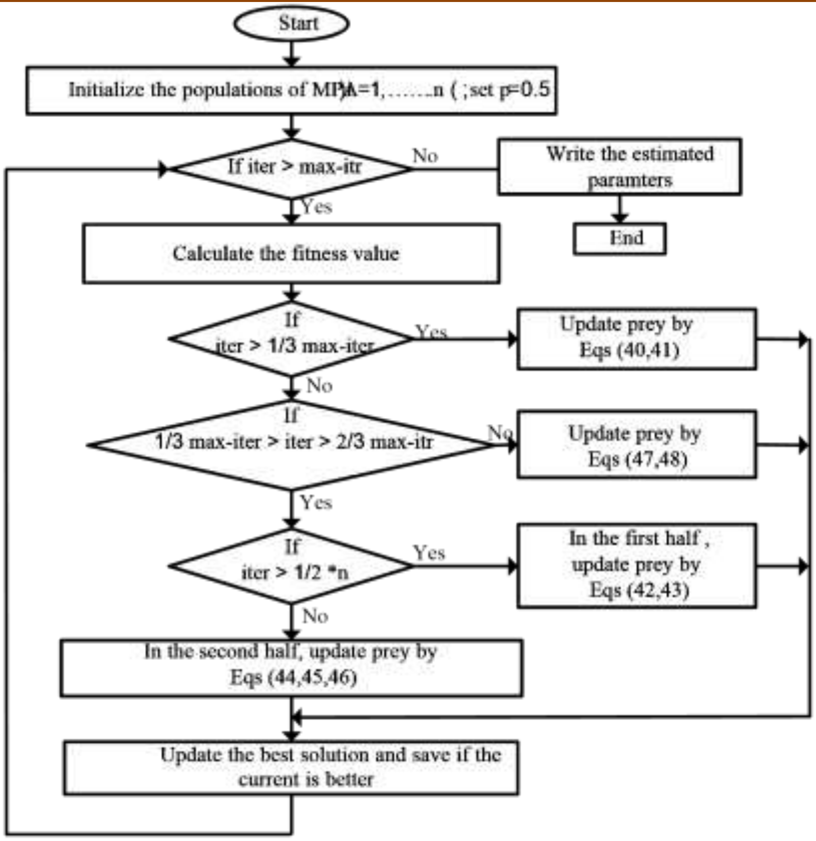

Fig. 2 Flowchart of marine predator algorithm

3.2 SALP SWARM ALGORITHM (SSA)

The main inspiration of salp is the swarming mechanism of salps when exploring and searching for their nutrition sources in oceans. Salps belong to the family of salpidae. Their movement and tissues are similar to jellyfishes. Moreover, the shape of a salp is cylindrical with cavities at its ending and pushes the water out of its jellied body with internal feeding filters [57]. The flowchart of the SSA has been shown in Fig. 3.

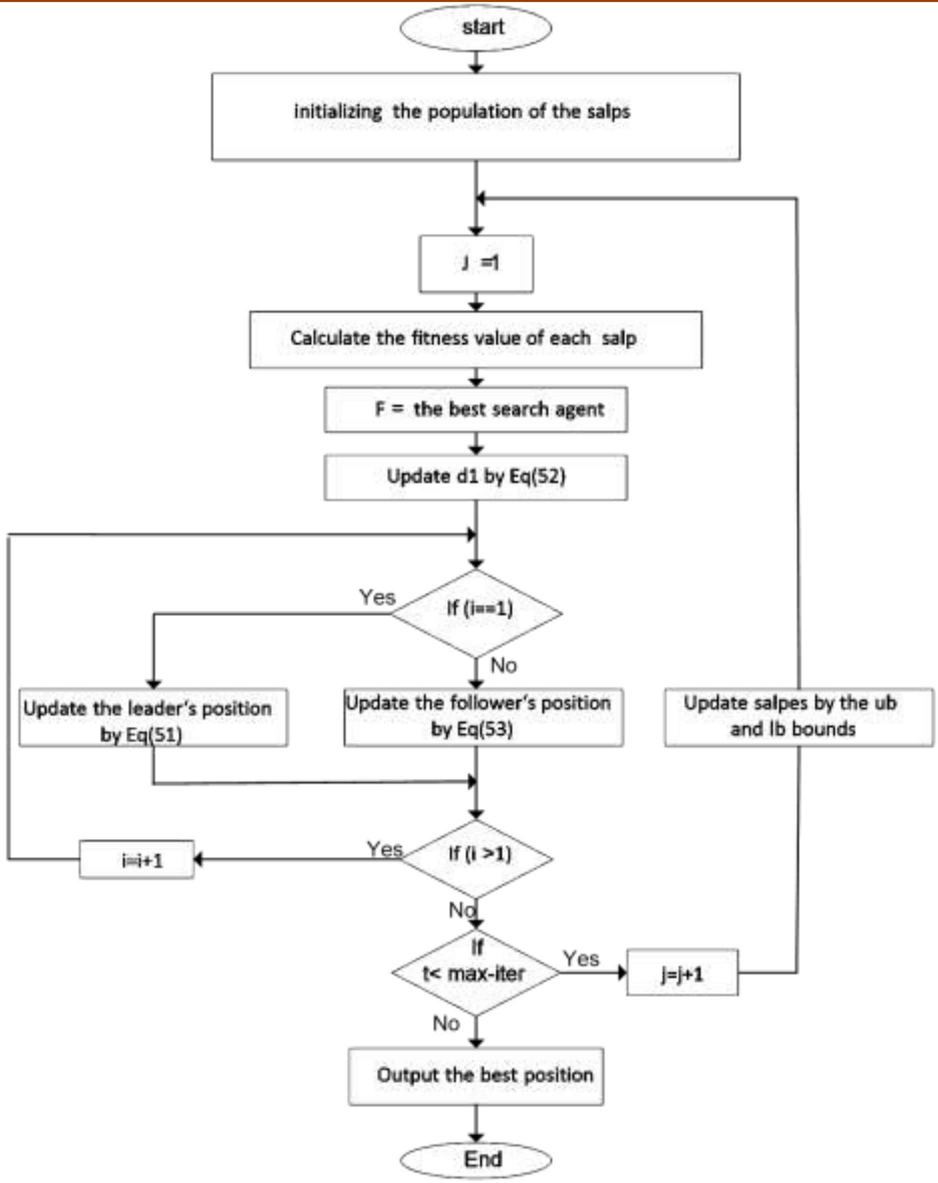

Fig. 3 Flowchart of the suggested SSA methodology.

4. Simulation Results

In this paper, the SSA has been evaluated on 12.66 kV IEEE 33-bus RDS [44]. The upper and lower bounds of voltage magnitude are taken as 1.05 and 0.95 p.u. for the systems under study. The weighting factors are taken as $\lambda_1 = 0.5$, $\lambda_2 = 0.4$, and $\lambda_3 = 0.1$ [44]. The cost coefficients are selected as $\kappa_1 = 4$ \$/kW and $\kappa_2 = 5$ \$/kW based on [44], where κ_2 is considered the cost of RDGs for installation and maintenance. A B/F sweep load flow is calculated to obtain the voltage shape and minimize the power losses. The sensitivity factors have been applied in this study to choose the candidate buses in RDS. The buses having VSF lower than 1.01 p.u. are defined the candidate nodes for RDGs installation. Then the proposed optimization method has been employed to generate the optimal allocation and sizing of RDGs from the selected buses. The Maximum iteration, Search agent number are 100 and 70 respectively. $\boldsymbol{V_{min}}$, and $\boldsymbol{V_{max}}$ boundaries are 0.95 and 1.05 respectively. Moreover, [$\boldsymbol{P_{DG\_min}}$, $\boldsymbol{P_{DG\_max}}$] are 0 and 2229 respectively. There is a case of study are employed in the standard system of 33-bus IEEE distribution systems.

The prepared methodologies are tested on IEEE 33-bus RDS [44]. For the test system under study the base voltage is taken as 12.66 KV and the base apparent power is adjusted at 100 MVA. The number of RDG is chosen to be three units for optimization. The optimal placement of three RDG in the IEE-33-bus test system is presented in Fig. 4.

Before injecting DGs on the distribution network, the total real power loss is recorded as 210.997 kW while the minimum recorded value of voltage magnitude is 0.9038 p.u. and reached at bus 18. From Table 1, the lowest VSF with highest LSF values of IEE 33-bus are introduced to determine the suitable buses for RDGs installations. Therefore, SSA algorithm and other methods have been applied on the first 10 rows. The calculated results of SSA and other optimization techniques for the IEE 33-bus are reported in **Error! Reference source not found.**. From this table, the most candidate buses that will have noticeable impacts on the distribution system with RDGs are identified as 8, 13, and 31.

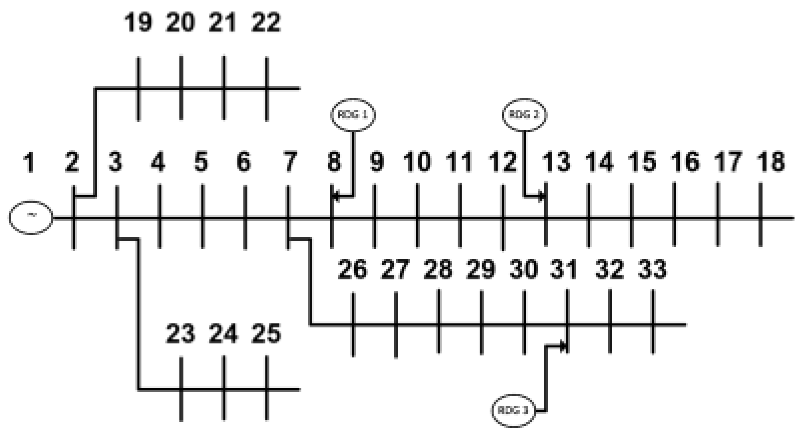

Fig. 4 Single line diagram of IEE 33-bus system and optimal location of three RDG units.

The optimum capacities of these critical nodes are 467.84 kW (8), 631.09 kW (13) and 752.77 kW (31), respectively with 1851.558 kVA total apparent power, at unity power factor (PV system). In comparison with the technique of MPA, the total power losses obtained by SSA is minimized from 210.98 to 84.7475kW, which higher than the other one.

From the optimization attainments, the reader can notice that applying the SSA generated the higher value of the RDG size compared to other techniques. To assess the performance of the SSA algorithm, the convergence trends of all suggested algorithms are compared, from which the superiority of SSA to reach the optimum solution in less iterations is proved, as shown in Fig. 5.

The radar plot presented in Fig. 6 illustrates the enhancement of the voltage profile in accordance with integrating the RDGs in the best locations of IEEE 33-bus system. It is shown from the figure that the voltage profile improvement is more noticeable in the case of SSA algorithm compared to the others. Therefore, SSA efficiently achieve the optimal allocation and sizing of RDGs with the highest reduction in total operating cost and power losses. Fig. 7 introduces the performance of all algorithms as compared to SSA. The voltage deviation index(ΔVD) and the power losses index have been minified highly in SSA technique than MPA, GWO, IGWO, and SOA, but their operating cost (ΔOC) is over than in the other algorithms.

Finally, the numerical results concluded that SSA is the most suitable method to obtain the maximum reduction in power loss and improving the voltage shape of the system.

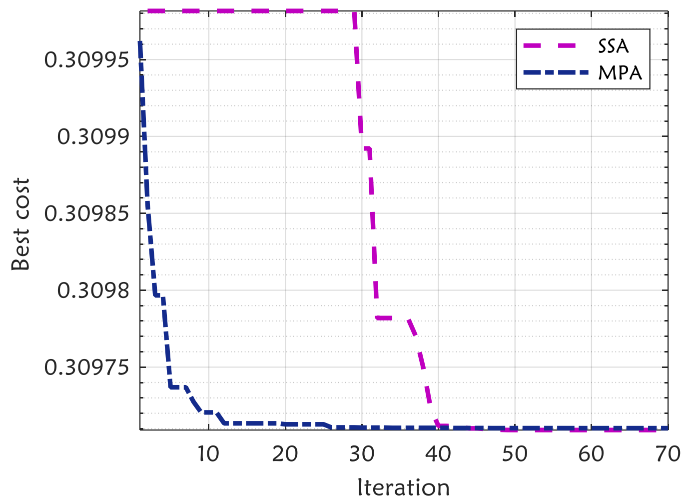

Fig. 5 Convergence curve for integrating RDG (PV system) with the two techniques in IEEE 33-bus.

Table 1 Accomplishments of two methods for IEEE 33- bus.

Items	***Normal Case***		
		SSA	*MPA*
Total losses (kw)	210.98	84.7475	84.7803
Loss reduction%	–	59.83%	59.82%
V worst (**Pu**), **bus**	0.9038, (18)	0.9637, (18,33)	0.9636, (18,33)
Optimal location and size of DGs (**kw**)	–	(8)467.84 (13) 631.09 (31) 752.77	(8) 470.46 (13)628.41 (31) 750
SDG (**KVA**)	–	1851.558	1848.411
TOC ($)	–	9597.1	9583.5
ΔOC		0.8611	0.8599
ΔPlDG	–	0.4182	0.4184
ΔVD	0.0962	0.0363	0.0364

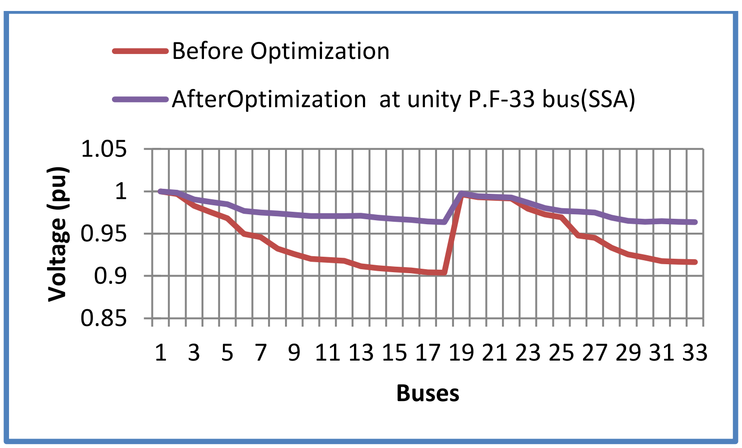

Fig. 6 Voltage profile with adding PV units in 33-bus system using the first Optimization algorithm.

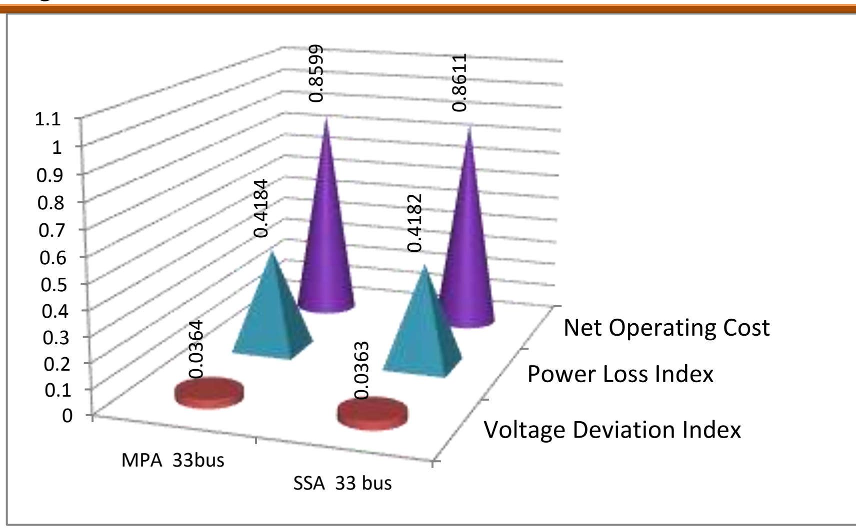

Fig. 7 Evaluation of different indicators for IEE 33-bus system.

5. Conclusion

In this paper, the proposed salp swarm algorithm (SSA) and marine predictor algorithm (MPA) have been presented introduced to select the optimal placement and capacity of RDGs in the radial distribution systems (RDS). Moreover, the sensitivity factors are utilized by verifying the most candidate buses that are needed for optimum allocation of PV units in distribution networks. Moreover, the effectiveness of the proposed optimization methods has been recognized on 33-bus IEEE RDS under different scenarios. Additionally, the results obtained from the suggested technique were compared with other algorithms to confirm its validation. The results demonstrated that the recommended SSA approach can be capable of lessening the overall operational payments, lowering active power losses, and boosting the voltage profile associated with the other one.

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