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Optimal Assimilation of Distributed Generation in Radial Power Distribution System Using Hybrid Approach

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Abstract
The performance of power distribution systems (PDS) has improved greatly in recent times ever since the distributed generation (DG) unit was incorporated in PDS. DG integration effectively cuts down the line power losses (PL) and strengthens the bus voltages (BV) provided the size and place are optimized. Accordingly, in the present work, a hybrid optimization technique is implemented for incorporating a single DG unit into radial PDS. The proposed hybrid method is formed by integrating the active power loss sensitivity (APLS) index and whale optimization meta-heuristic algorithm. The ideal place and size for DG are optimized to minimize total real power losses (TLP) and enhance bus voltages (BV). The applicability of the proposed hybrid technique is analyzed for Type I and Type III DG installation in a balanced IEEE 33-bus and 69-bus radial PDS. Optimal inclusion of type I and III DG in a 33-bus radial test system cut down TLP by 51.85% and 70.02% respectively. Likewise, optimal placement of type I and III DG reduced TLP by 65.18%, and 90.40%, respectively for 69-bus radial PDS. The impact of DG installation on the performance of radial PDS has been analyzed and a comparative study is also presented to examine the sovereignty of the proposed hybrid method. The comparative study report outlined that the proposed hybrid method can be a better choice for solving DG optimization in radial PDS.

Keywords
Distributed Generation, Power Distribution System, Power Losses, Whale Optimization Algorithm.

I. Introduction

Electricity consumers around the globe are powered from a centralized power plant through transmission and distribution systems. The customers are directly connected to the distribution system (DS). Large numbers of customers are powered through DS. Hence, it encounters more power losses (PL) & voltage drops (VD), and voltage instability than transmission power networks because of its high R/X ratio and large customers. As a consequence, the performance of DS degraded. Also, the consumers connected to DS experience the aforesaid problem. Therefore, in recent times the focus has been shifted towards assimilation of dispersed or distributed generation (DG) in DS for making electrical power networks efficient, reliable, and secure. DG placement has emerged dramatically because of its knack for generating electricity at or near load centres [1]. DG is considered to be more efficient than conventional power generation since it doesn't require transmission or distribution lines for transferring power to customers. Also, DG placement offers a number of benefits including PL & VD minimization, stability & reliability enhancement, and fuel cost reduction. However, these benefits can be achieved only if DG is located at a suitable site and size in PDS. Var-

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TABLE I.
NOMENCLATURE AND ABBREVIATION

NOMENCLATURE			
w_1 & w_2	Weightage factors	v_r	Rated wind velocity
f_1 & f_2	Objective functions	v_{cout}	Cut-out wind velocity
$TLP_{beforeDG}$	TLP of PDS prior DG allocation	P_L	Active power demand
V_1	Substation bus voltage	Q_L	Reactive power demand
V_i	Bus voltage profile	R	Resistance
V_{min}	Desired minimum bus voltage of PDS	X	Reactance
V_{max}	Desired maximum bus voltage of PDS	V_{norm}	Normalized voltage
P & Q	Real and reactive power respectively	A &C	Coefficient vectors
P_{DG}	Optimized real power capacity of DG	l, p & r	Random numbers
Q_{DG}	Optimized reactive power capacity of DG	B	Constant
n	Number of buses of PDS	P_{loss}	Real power loss
G_r	Rated solar irradiance refers to earth's surface	Q_{loss}	Reactive power loss
G	Solar irradiance at the optimal DG site	P_{DG}^{min}	Minimum real power penetration capacity of DG
v	Wind velocity at optimal DG site	P_{DG}^{max}	Maximum real power penetration capacity
N	Number of distribution lines of PDS	v_{cin}	Cut-in wind velocity
Q_{DG}^{min}	Minimum reactive power capacity of DG	Q_{DG}^{max}	Maximum reactive power penetration capacity of DG
$S_{L,rated}$ &S_L	Rated and actual apparent powers of distribution line	P_r	Rated output power of type I DG
ABBREVIATION			
MOF	Multi-objective function	DS	Distribution system
WOA	Whale optimization algorithm	ALO	Ant lion optimizer
PDS	Power distribution systems	PFA	Power flow assessment
DG	Distributed generation	PV	Photovoltaic
APLS	Active power loss sensitivity	WT	Wind turbine
RDS	Radial distribution systems	RPL	Real power loss
PSO	Particle swarm optimization	ECOA	Enhanced coyote optimization algorithm
GWO	Grey wolf optimization	GA	Genetic algorithm
BSOA	Backtracking search optimization algorithm	SOA	Shark optimizer algorithm
ROA	Rider optimization algorithm	BFS	Backward /forward sweep

ious optimization studies were implemented using different methods to quantify the benefits of optimal DG placement. The detailed literature about various methodologies applied to obtain a feasible solution for a complex DG optimization problem is presented below.

An analytical optimization methodology was employed in [2] to discover the optimal position and size of DG for reducing the TLP of radial PDS. A simple iterative Newton raphson (NR) power flow technique has been introduced in [3] to optimize DG position and capacity in DS. The authors [4] have optimized multiple DG units in RDS by proposing a methodology based on a particle swarm optimization (PSO) algorithm for reducing TLP. An optimization technique using grey wolf optimization (GWO) algorithm has been introduced to allocate DG of type I and II in radial PDS [5]. A multi-objective integrated optimization approach was proposed in [6] to optimize DG placement. The proposed integrated technique was formed by combining the features of bat and shuffled frog leaping algorithms. The discrete ABC algorithm was effectively applied in [7] for simultaneous DG allocation and network reconfiguration to cut down TLP and extend the system loadability limit. Backtracking search optimization algorithm (BSOA) [8] and Ant Lion Optimizer (ALO) [9] based approaches were suggested for allocation of DG in different RDS. A modified form of PSO algorithm was developed and executed in [10] to optimize DG for minimizing the TLP of RDS. An ant lion optimization meta-heuristic technique was implemented in [11,12] to optimize different DG units in PDS for reducing real power losses. Rider optimization algorithm (ROA) was introduced in [13] to solve the DG optimization problem considering power generation uncertainty. The ideal position and size of DG were figured out using an enhanced coyote optimization algorithm (ECOA) [14], Genetic algorithm (GA) [15], PSO and DE algorithms [16]. A novel DG optimization technique was introduced using shark optimizer algorithm (SOA) to optimize single and multiple DG unit's site(s) and size(s) in different radial PDS [17].

As aforementioned earlier, different techniques were proposed and executed to obtain a feasible solution for a DG placement problem. However, for solving this complex DG optimization problem the aforementioned techniques faced several setbacks including inaccurate results, high computation time and local optima stagnation. Thus, in order to curb these drawbacks, a hybrid optimization technique is proposed in the present work by integrating APLS index and WOA. The computation of APLS index effectively reduces the search space for WOA. Thus global optimal solution can be achieved at a better convergence rate. Furthermore, up to the knowledge of the author(s), the proposed integrated DG optimization approach has not been employed by any researcher in the literature. The validation of the proposed hybrid technique has been executed in MATLAB simulation software for symmetrical 33-bus and 69-bus IEEE radial PDS. Besides, the efficacy of the suggested hybrid technique is explored by correlating the test results with other popular optimization techniques.

The remaining part of the research work is presented as follows: Section II. explains the mathematical modelling and application of the proposed APLS index-WOA hybrid technique for a DG placement problem. Section III. outlines the objective functions framework and DG modelling. Section IV. presents and elaborates on the optimized test results of radial PDSs. The research outcome of the proposed optimization technique is presented and concluded in Section V. .

II. Hybrid Technique: Modelling

The fundamental concept and modelling of hybrid technique proposed in the present work is described in this section.

A. *DG positioning: Active power loss sensitivity index approach*

Active power loss sensitivity (APLS) index is a sensitivity factor approach applied for identifying optimal/potential sites for DG assimilation. In this work, the APLS index is utilized for identifying potential buses for DG integration. Besides locating the potential buses for DG incorporation, the APLS index also significantly minimizes the search boundary of DG optimization problem. This substantially improves the convergence rate of the optimization algorithm. APLS index for a radial PDS is assessed using (1) [13]. APLS index values for radial PDS are computed with the aid of PFA results.

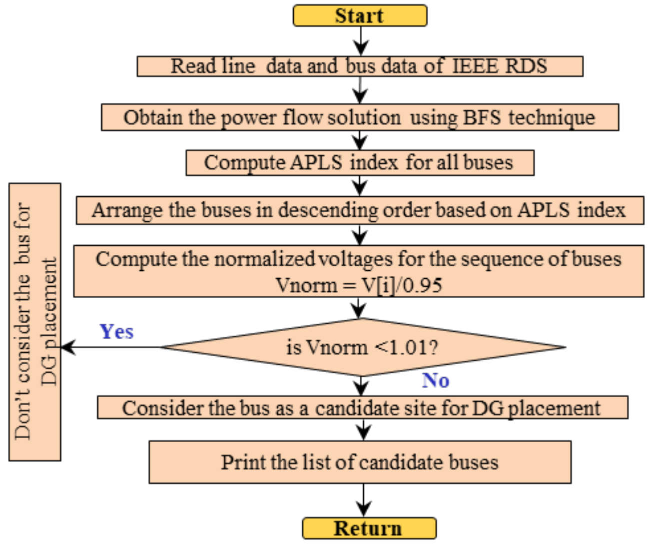

Fig. 1. Algorithm for candidate bus selection based on APLS Index

$$APLS\ Index = \frac{2Q_{i+1}.R_k}{|V_{i+1}|^2} \tag{1}$$

The algorithmic illustration of potential bus identification for DG assimilation using the APLS index is shown in Fig. 1. APLS index values for IEEE 33-bus and 69-bus radial PDS is exhibited in Fig. 2 and Fig. 3, correspondingly.

For 33-bus radial PDS, the computation of APLS index has curtailed the search space by 36.36%. Likewise, for 69-bus radial PDS, the search space is cut down by 69.56%. i.e.,

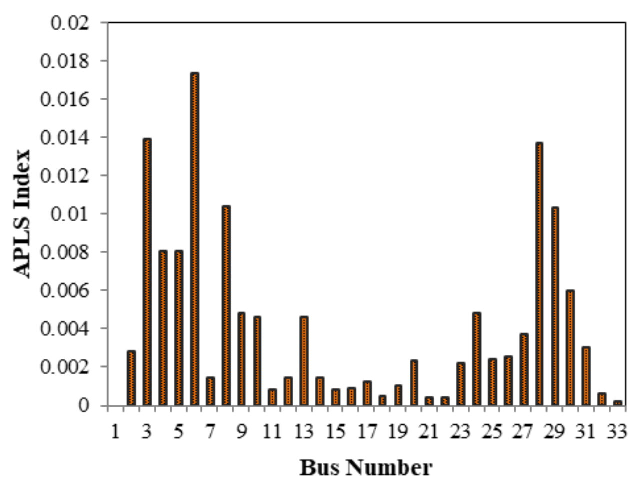

Fig. 2. APLS index for IEEE 33 bus radial PDS

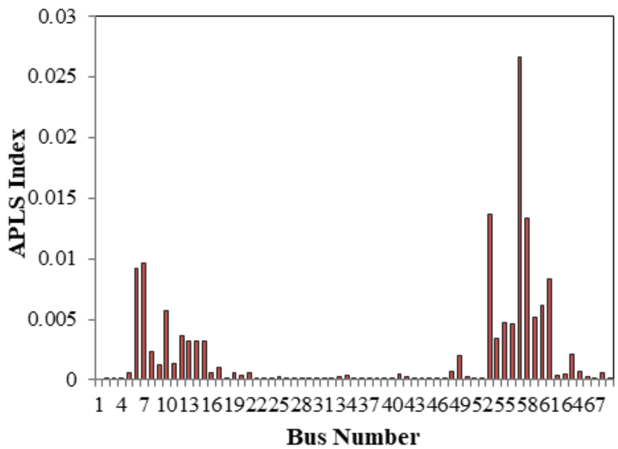

Fig. 3. APLS index for IEEE 69 bus radial PDS

a total of 12 in 33-bus radial PDS and 48 in 69-bus radial DS were excluded from the search area. The exclusion has been made referring to the normalized voltage (V_{norm}). The buses having normalized voltage less than 1.01 are considered qualified locations for DG assignment.

B. Whale optimization algorithm: An overview

Hof and Van Der Gucht, renowned scientists, discovered that a whale's brain cells are similar to human cells and its cells count outnumbered human cells [18]. The humpback type of whale uses these cells efficiently for hunting its prey and such behavior is termed a bubble-net feeding technique. Bubble-net feeding technique is mathematically modeled in two stages as follows [19].

1) Prey searching and encircling of prey

The whale's ability to search for food (prey) is represented using (2) and (3).

$$D = |C.X_{rand} - X| \tag{2}$$

and

$$X(t+1) = X_{rated} - A.D \tag{3}$$

Where

$$A = 2.a.r - a \tag{4}$$

and

$$C = 2.r \tag{5}$$

If A< 1, then

$$D = |C.X^*(t) - X(t)| \tag{6}$$

and

$$X(t+1) = X^*(t) - A.D \tag{7}$$

Equations (2) and (3) exemplify the whale's random search for food when $A \geq 1$. Likewise, (6) and (7) represent the encircling of prey when $A < 1$. This process is called a shrinking mechanism and it characterizes the attacking nature of whales.

2) Spirally updating position

The position of whale after hunting is updated using (8).

$$X(t+1) = \begin{cases} X^*(t) - A.D, & \text{if } p < 0.5 \\ D.e^{bl}.cos2\pi l + X^*(t), & \text{if } p \geq 0.5 \end{cases} \tag{8}$$

3) Implementation of hybrid optimization technique

The implementation of the proposed hybrid methodology for a DG optimization problem is detailed in various steps as follows.

1. Acquire the required radial PDS data for the PFA study.
2. Execute power flow using the BFS method and compute TLP and bus voltage.
3. Compute the APLS index and identify a list of candidate bus locations for DG placement.
4. Feed the list of candidate bus locations to WOA and initialize populations = 30, iteration count = 100 and DG size (search agent) boundary limits. If DG size goes beyond the specified bound, then normalize its size within the specified limits.
5. Compute the fitness value of MOF for all search agents using (9) and find the best agent (initial).
6. Update l, a, A, C and p for every search agent by (4) and (5).
7. If $p < 0.5$, then move to next step or else move to Step 9.
8. Replace the initial best agent by (7) if $|A| < 1$. Otherwise, determine and update the search agent by (3).
9. Upgrade the search agent position by (8).
10. Print the result, if a convergence criterion is reached. Otherwise, move to Step 5.

Figure 4 illustrates the flowchart for the proposed hybrid optimization technique.

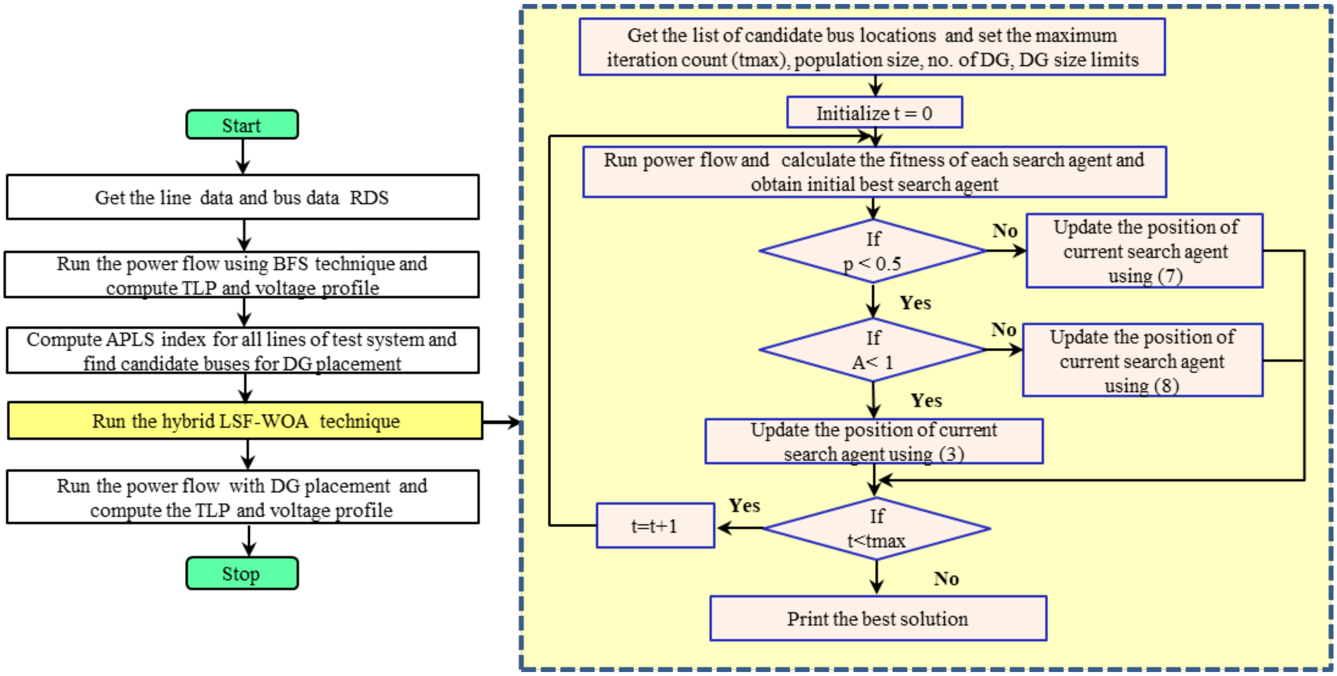

Fig. 4. Flowchart of proposed hybrid technique

III. Objective Function Framework

A multi-objective function (MOF) for a DG optimization problem in the present work is developed to cut down TLP and to increase bus voltage magnitude of PDS. The expression for MOF is represented as weighted factors and is given in (9) [11].

$$MOF = min(w_1.f_1 + w_2.f_2) \tag{9}$$

Where

$$f_1 = \frac{TLP_{afterDG}}{TLP_{beforeDG}} \tag{10}$$

and

$$f_2 = max(V_1 - V_i) \tag{11}$$

The MOF is optimized in line with various operating constraints [11] of radial PDS including bus voltage, DG power and line capacity.

A. Constraints

1) Bus voltage (BV) constraint

$$0.95p.u(V_{min}) \leq V_i \leq 1.05p.u(V_{max}) \tag{12}$$

2) Power balance constraint

$$P_{DG} \leq 75\% \left(\sum_{i=1}^{n} P_i + \sum_{k=1}^{N} P_{loss,k} \right) \tag{13}$$

$$Q_{DG} \leq 75\% \left(\sum_{i=1}^{n} Q_i + \sum_{k=1}^{N} Q_{loss,k} \right) \tag{14}$$

3) DG real power generation constraint

$$P_{DG}^{min} \leq P_{DG} \leq P_{DG}^{max} \tag{15}$$

4) DG reactive power generation constraint

$$Q_{DG}^{min} \leq Q_{DG} \leq Q_{DG}^{max}) \tag{16}$$

5) Line capacity constraint

$$S_L(i) \leq S_{L,rated}(i) \tag{17}$$

B. Distributed generation modelling

Distributed generation (DG) is a distinctive approach employed for power generation near the load centre. DG technology deploys different energy resources for power generation. DG resources are clustered into four classes [20] in line with their capability to inject/absorb active (P) & reactive (Q) power. Table II presents the different categories of DG unit(s).

DG units are modelled as per the recommendation of IEEE 1547 standards [21]. For the present work, type I and type III DG are characterized as constant P model (unity p.f.) and constant PQ model (0.866 p.f.), respectively.

TABLE II.
CLASSIFICATION OF DG

Type	Features
I	Injects P only
II	Injects Q only
III	Injects P and Q
IV	Injects P and but absorbs Q

1) *Type I DG modelling*

Equation (18) describes the output power (P) rating of a type I DG unit [21]. For the present work, the solar PV system is modeled as type I DG.

$$P = \begin{cases} P_r * \left(\frac{G}{G_r}\right), & 0 \leq G \leq G_r \\ P_r, & G_r \leq G \end{cases} \tag{18}$$

2) *Type III DG modelling*

For the present work, the wind turbine (WT) system is modeled as type III DG. Equations (19) and (20) illustrate the real (P) and reactive (Q) power output of type III DG [21].

$$P = \begin{cases} 0, & 0 \leq v \leq v_{cin} \\ P_r * \left(\frac{v - v_{cin}}{v_r - v_{cin}}\right), & v_{cin} \leq v \leq v_r \\ P_r, & v_r \leq v \leq v_{cout} \end{cases} \tag{19}$$

$$Q = P * tan\left(cos^{-1}(p.f._{DG})\right) \tag{20}$$

3) *Power flow assessment in radial PDS*

The power flow assessment (PFA) in electrical power networks is essential for utilities to determine various parameters including real & reactive power flows, line power losses, bus voltage, etc. Consider a typical radial PDS with 'n' buses and 'N' branches as illustrated in Fig. 5.

Active (P_{i+1}) and reactive power (Q_{i+1}) flows of radial PDS are computed using (21) and (22), respectively.

$$P_{i+1} = P_i - P_{L(i)} - R_k * \frac{P_i^2 + Q_i^2}{|V_i|^2} \tag{21}$$

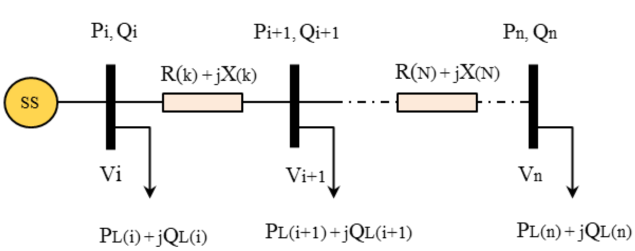

Fig. 5. Radial PDS

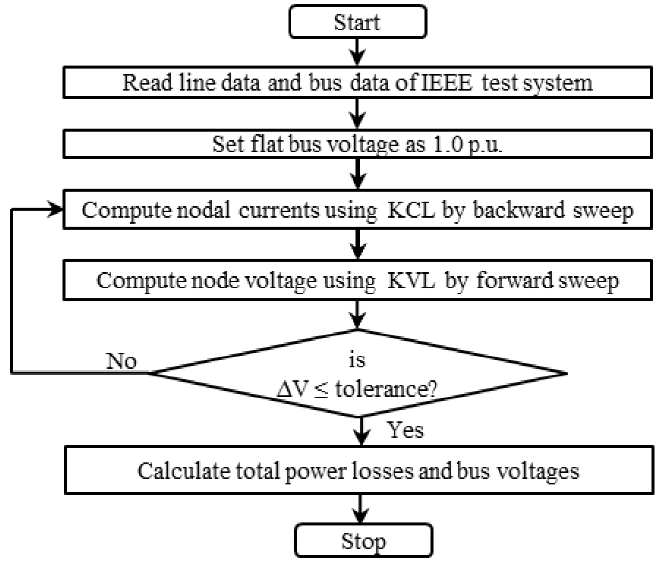

Fig. 6. BFS power flow algorithm flowchart

$$Q_{i+1} = Q_i - Q_{L(i)} - X_k * \frac{P_i^2 + Q_i^2}{|V_i|^2} \tag{22}$$

Where, i = 1, 2... n and k = 1, 2... N.

The bus voltage (BV) of radial PDS is calculated using (23) [22].

$$|V_{i+1}|^2 = |V_i|^2 - 2(R_k.P_i + X_k.Q_i) + (R_k^2 + X_k^2) * \frac{P_i^2 + Q_i^2}{|V_i|^2} \tag{23}$$

The real power loss (RPL) along a distributed line 'k' is calculated as in (24) [22].

$$RPL_k = R_k * \frac{P_i^2 + Q_i^2}{|V_i|^2} \tag{24}$$

Therefore, total real power losses (TLP) of a radial PDS is computed using (25).

$$TLP = \sum_{k=1}^{N} RPL_k \tag{25}$$

The popular PFA methods of transmission power networks do not deliver adequate solutions for radial PDS. Hence, a backward/forward sweep (BFS) algorithm-based power flow calculation approach is implemented for radial PDS [23].

PFA using BFS technique involves two phases of calculation. In the first phase of calculation, the magnitude of the branch current is calculated. The calculation instigates from the last bus and proceeds backward towards the slack bus.

TABLE III.
CHOICE OF WEIGHTAGE FACTORS

Case	w_1	w_2	Fitness value
I	0.6	0.4	0.2960
II	0.65	0.35	0.3192
III	0.7	0.3	0.3423
IV	0.75	0.25	0.3654
V	0.8	0.2	0.3885
VI	0.85	0.15	0.4116
VII	0.9	0.1	0.4347
VIII	0.95	0.05	0.4578

Hence, it is termed a backward sweep. Whereas the second phase of calculation involves the computation of bus voltage. In contrast to the backward sweep, this phase of calculation is initiated from slack bus and proceeds forward toward the end bus of RDS. This phase is termed a forward sweep. The algorithmic illustration of PFA using the BFS method is presented in Fig. 6.

IV. Test Results and Discussion

The optimized outcome of test systems for the proposed method is presented and detailed in this section. The efficacy of the suggested hybrid method in the present work was realized with optimal single DG placement (type I and type III) in 33-bus and 69-bus IEEE radial PDSs. The necessary programming for the proposed hybrid approach was coded and executed in MATLAB version 2020b.

The appropriate weightage factors (w_1 and w_2) for MOF f_1 and f_2 are chosen according to their importance. In this work, more importance is given to f_1 than f_2; hence w_1 should be greater than w_2. The apt choice of values for w_1 and w_2 was discovered by placing a DG unit in RDS (IEEE 33-bus). The values of w_1 and w_2 which produce minimum fitness value are considered suitable weightage factors. The fitness function value for different combinations of w_1 and w_2 is listed in Table III.

The lowest value for the objective function was obtained for case I with w_1 and w_2 as 0.6 and 0.4 respectively. The DG size was optimized by excluding the stochastic nature of environmental effect.

A. 33-bus IEEE radial PDS

Single-line schematic representation of a 33-bus radial PDS is presented in Fig. 7. The necessary data (line and bus) required for the PFA of this radial PDS is referred to [23]. This radial PDS carries a net real power load of 3720 kW and a net reactive power load of 2300 kVAr. The feeder delivers power at a voltage of 12.66 kV.

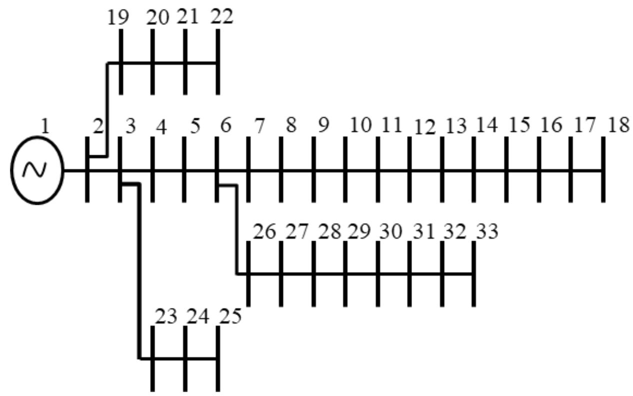

Fig. 7. 33-bus IEEE radial PDS

1) Prior DG placement

PFA was executed on a scale of 100 MVA power rating at 12.66 kV. The power flow assessment prior to DG placement has resulted in 210.98 kW of TLP, 143.12 kVAr of total reactive power losses (TLQ) and V_{min} of 0.9038p.u.

2) After DG placement

The optimized result of the proposed hybrid method for 33-bus radial PDS is presented in Table IV. WOA optimized the type I and type III DG with a capacity of 2437.5 kW and 2345.8 kVA, respectively at bus number 6.

The allocation of type I DG has brought down the TLP of the test system from 210.98 kW to 101.5 kW and V_{min} got better from 0.9038p.u to 0.9532p.u. Likewise, optimal deployment of type III DG has minimized TLP to 63.24 kW

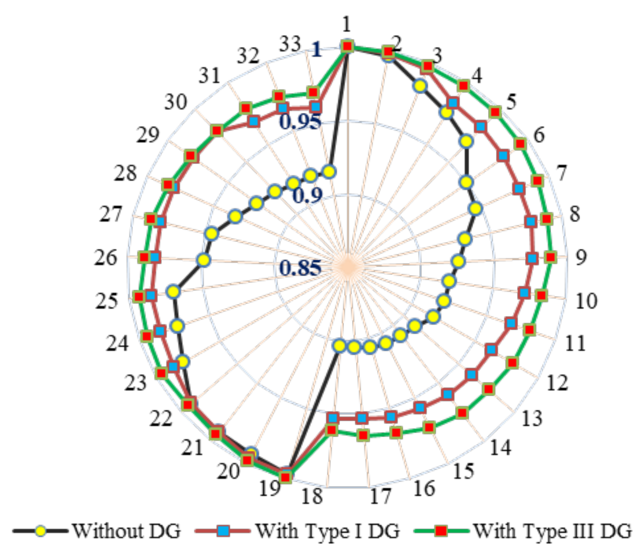

Fig. 8. BV of IEEE 33-bus radial PDS prior and following DG placement

TABLE IV.
IEEE 33 BUS PDS: TEST RESULTS

Simulation Outcome	Prior DG Placement	After DG Inclusion	
		Type I	Type III
TLP in kW	210.98	101.5	63.24
V_{min} in p.u.	0.9038	0.9532	0.9612
Optimal bus location	-	6	6
Optimal size (kW/kVA)	-	2437.5	2345.8
Percentage TLP reduction	-	51.85	70.02

and improved V_{min} to 0.9612p.u. Figure 8 presents the voltage magnitude for the 33-bus test system prior to and after DG placement. Also, WOA took seven and eight iterations respectively for optimal type I and type III DG placement to converge optimal results. The convergence curve of WOA for 33-bus radial PDS is displayed in Fig. 9.

A comparative analysis has been performed between the proposed and other optimization techniques and it is presented in Table V and Fig. 10. The suggested hybrid methodology-based allocation has cut down TLP by 51.85% and 70.02% for type I and type III DG, respectively. Deployment of type I DG via the proposed hybrid technique has provided maximum power loss reduction compared to other techniques cited in [3], [5], [11–17] ranging from 1.29 kW (min) to 35.25 kW (max). Similarly, for type III DG deployment these values varied from 1.9 kW (min) to 18.19 kW (max). Also, the proposed technique achieved better V_{min} than other techniques.

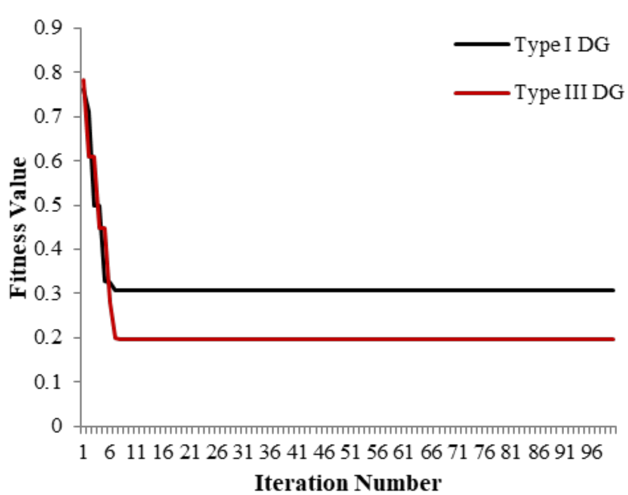

Fig. 9. Convergence curve of WOA for 33-bus radial PDS

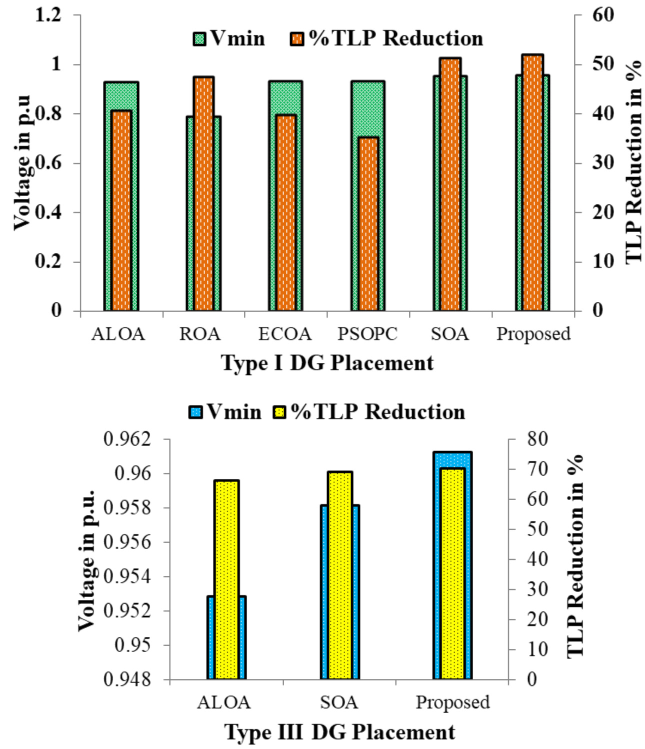

Fig. 10. Statistical results comparison for 33-bus radial PDS

B. 69-bus IEEE radial PDS

One-line schematic of 12.66 kV, 69-bus IEEE standard radial PDS is illustrated in Fig. 11. The test system includes 68 load buses which absorb a net real and reactive power of 3802 kW

TABLE V.
COMPARATIVE STUDY: IEEE 33-BUS PDS

Optimization technique	Optimal Size/Bus	TLP in *kW*	V_{min} in *p.u*
Type I DG Placement			
Analytical [3]	2490/6	111.24	NR
ALOA [11]	1542.7/30	125.16	0.9272
ROA [13]	2590.2/6	111.02	0.7886
ECOA [14]	1000/30	127.28	0.9285
GA [15]	2580/6	105.48	NR
PSOPC [16]	1000/15	136.75	0.9318
SOA [17]	2600/6	102.79	0.9525
Proposed	2437.5/6	101.50	0.9532
Type III DG Placement			
ALOA [12]	2238.8/6	71.75	0.9528
SOA [17]	2550/6	65.14	0.9581
GWO [5]	1000/30	81.43	NR
Proposed	2345.8/6	63.24	0.9612

TABLE VI.
IEEE 69 BUS PDS: TEST RESULTS

Simulation Outcome	Prior DG Placement	After DG Inclusion	
		Type I	Type III
TLP in kW	225	78.34	21.58
V_{min} in p.u.	0.9092	0.9624	0.9708
Optimal bus location	-	61	61
Optimal size (kW/kVA)	-	1876.58	2045.24
Percentage TLP reduction	-	65.18	90.40

and 2694 kVAr, respectively.

1) Prior DG placement

The line and bus data required for PFA is referred to in [23]. PFA was executed to compute line flows, power losses and bus voltages. The test system recorded 225 kW of TLP and V_{min} of 0.9092p.u prior DG placement.

2) After DG placement

The optimized result for 69-bus radial PDS is furnished in Table VI. The proposed hybrid technique optimized the DG at bus number 61 with a capacity of 1876.58 kW for type I DG and 2045.34 kVA for type III DG. The integration of DG has cut down TLP from 225 kW to 78.34 kW (type I) and 21.58 kW (type III). Also, the V_{min} of radial PDS got better from 0.9092p.u to 0.9624p.u and 0.9708p.u after type I and type III DG, respectively. The optimized solution was obtained with WOA at 8^{th} and 9^{th} iterations for type I and III DG placement, respectively. Figure 12 presents BV of 69-bus radial PDS after DG assimilation. The convergence curve of WOA for 69-bus radial PDS is shown in Fig. 13.

Table VII and Fig. 14 present a comparative study between the proposed and other optimization techniques. The proposed hybrid methodology has cut down TLP by 65.18% for type I DG and 90.40% for type III DG placement. The table of results exemplifies that the proposed hybrid technique achieved the highest percentage of power loss reduction compared to other techniques cited in [3], [5], [11–13], [16, 17]. Also, from the test results presented in Tables IV and VI, it was witnessed that optimal allocation of type III DG has pro-

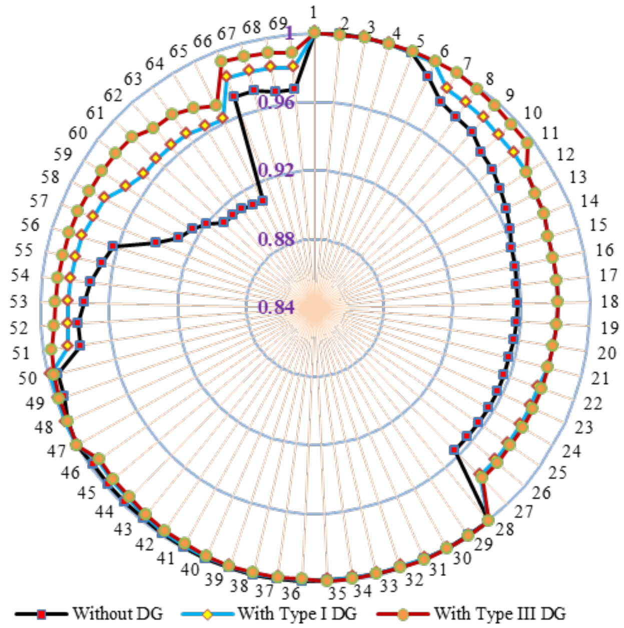

Fig. 12. Voltage magnitude of IEEE 69 bus radial PDS prior and following DG placement

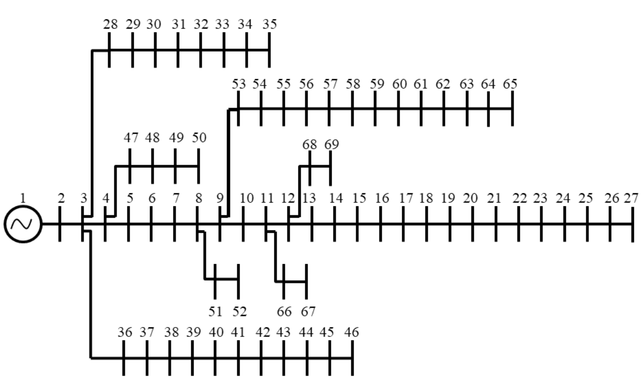

Fig. 11. 69-bus IEEE radial PDS

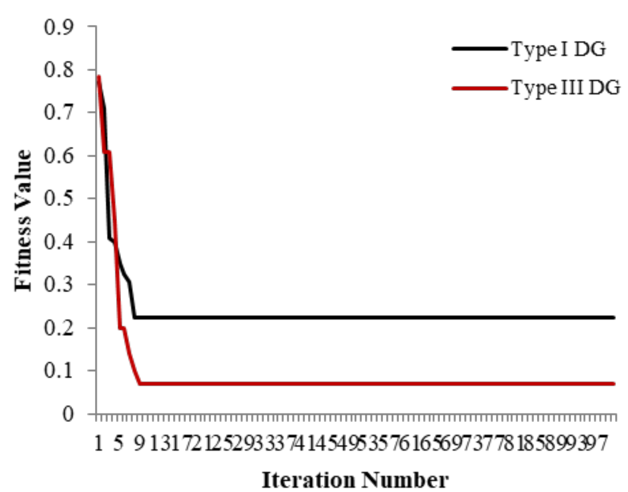

Fig. 13. Convergence curve of WOA for 69 bus IEEE radial PDS

TABLE VII.
COMPARATIVE STUDY: IEEE 69-BUS PDS

Optimization technique	Optimal size (kW/kVA)	Optimal location	TLP (kW)
Type I DG Placement			
Analytical [3]	1810	61	81.54
ALOA [11]	1800	61	81.77
ROA [13]	1872.7	61	83.19
GA [5]	1872	61	83.18
PSO [16]	1337.8	61	83.20
SOA [17]	1890	61	81.50
Proposed	1876.6	61	78.34
Type III DG Placement			
ALOA [12]	2227.9	61	23.16
ROA [13]	1828.5	61	23.16
SOA [17]	2250	6	23.15
Proposed	2045.3	61	21.58

vided much better results than type I DG. This is generally because of the reactive power support provided by type III DG besides the real power injection. Where type I DG only injects real power into the distribution power grid.

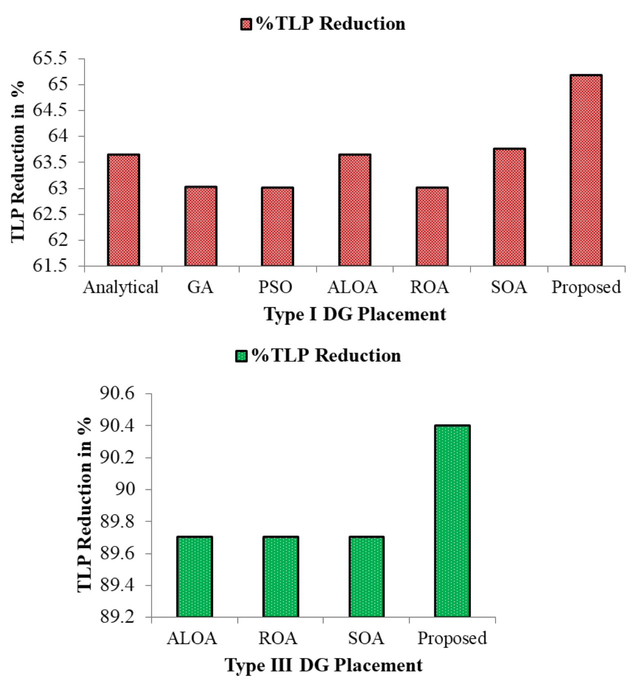

Fig. 14. Statistical results comparison for 69-bus radial PDS

V. CONCLUSION

In this paper, a hybrid technique using a meta-heuristic whale optimization algorithm and active power loss sensitivity index has been applied to solve a single DG optimal placement problem in a radial power distribution system. The proposed technique optimized the site and size for type I and type III DG to minimize a multi-objective problem including minimization of total real power loss (TLP) and voltage deviation (VD). The efficacy of the proposed hybrid technique was explored on a standard symmetrical IEEE 33-bus and 69-bus radial PDS. Optimal assimilation of type I DG in 33-bus and 69-bus test systems cut down TLP by 51.85% and 65.18%, respectively. Also, the minimum bus voltage (V_{min}) got better to 0.9532p.u and 0.9624p.u for 33-bus and 69-bus radial PDS, respectively. Likewise, type III DG placement reduced TLP by 70.02% and 90.40%, respectively for 33-bus and 69-bus radial PDS. Furthermore, the V_{min} of the corresponding test system enhanced to 0.9612p.u and 0.9708p.u from a base value. A statistical comparative study was performed between the proposed and other optimization approaches on the basis of percentage TLP reduction and V_{min}. The statistical report exemplified that the proposed hybrid technique achieved a maximum percentage of TLP reduction and better voltage profile enhancement than other techniques. Besides, it was witnessed that optimal allocation of type III DG unit contributed much better in minimizing the multi-objective function value than type I DG unit.

CONFLICT OF INTEREST

The authors have no conflict of relevant interest to this article

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