Optimal Allocation and Sizing of Distributed Generation in IEEE-85 BUS System Considering Various Load Models Using Multi-objective Metaheuristic Algorithms

Sumeet Kumar and Ashwani Kumar

Abstract Present-day distribution systems are bidirectional due to the integration of renewable energy sources and distributed generation. For efficient operation of the distribution systems, the loss reduction and voltage management are of the essential operational requirements. In India, the overall transmission and distribution losses for the 2018–2019 financial year were 20.66% and that needs major concerns for better efficiency of the system. The distribution system experiences voltage deviation and stability issues due to the improper management of the reactive power management and load growth. In order to limit these losses and better voltage profile, the system shall be planned with better control of reactive power and reduced losses. The losses and voltage can be better managed with the distribution generation integration into the existing system with optimal location and size. In this paper, DGs (distributed generation) in the radial distribution network have been optimally located and sized to minimize the line loss and enhance the voltage profile. This study aims to develop a multi-objective optimization model that considers various distribution load models while maximizing both technical and financial advantages. The appropriate positioning and sizing of DG resources in distribution networks are significantly influenced by load models and therefore, different load models have been incorporated in this study. The multi-objective function (MOF) contains the cost of active power loss reduction, voltage deviation enhancement, and the cost of installing DGs. The effects of four different load models are investigated using metaheuristic techniques. The study is carried out on an IEEE 85-bus radial distribution network as a test system. A comparison of results using Whale Optimization (WO), Grey Wolf Optimization (GWO), and Firefly Algorithm (FA) is analyzed to verify the effectiveness of the applied techniques.

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1 Introduction

The complicated structure of the demand–supply, rapidly increasing power consumption, and contemporary electrical gadgets make it difficult to maintain economical and reliable distribution systems. In the competitive power market, the sustainability of the distributed generation (DG) resources is playing key role for the better operation and management. The main objective of a modern power distribution system is to provide quality and uninterrupted power supply to each consumer. Therefore, an effective distribution control system should increase system efficiency overall through loss reduction and management of power quality. A passive distribution method was used in the past, however present distribution n system is having bidirectional power flows due to the integration of renewable energy sources and distributed generation meeting the increasing load demand of various types. However, there are numerous challenges in the competitive regime of distribution systems in terms of the losses, voltage and reactive power requirements and compensation; DGs cost, distributed energy resources and their location, and energy storage facilities, which require fundamental change in the operation and management of the network. Distributed energy resources location and sizing, dispatching of the units, practical load consideration, load growth are key issues that require attention for the distribution system planner.

There are a number of cost-effective solutions available to enhance the operation and performance of distribution networks. These methods include strengthening feeders, rearranging networks, installing dispersed generation, placing reactive power sources, and integration of distributed generation with renewable sources. The planning and operation of distribution system require its efficient operation and management with reduced losses and higher efficiency. With the introduction of the competitive power system structure, it has added the new sources of power generation along with conventional sources in the system for sustainable green energy. The distribution network thus has grown with bidirectional power flow acting as active distribution system. The additional components, increasing load growth, the customers, and electricity providers are affected by distributed generation in terms of voltage profile, power flow, continuity, stability, power supply quality, and short circuit level [1]. To overcome these effects there is a need to address the issues of operation and management with distributed generation having proper location and sizes. Various optimization techniques are being used for optimal placement and sizing of the distributed generation. In certain ways, the distribution network operator has almost no effect on the placement and sizing of DG because the choice to locate it depends on stockholders, the availability of the fuel source, land rights of way, and climatic circumstances [2]. However, these DGs require the proper integration in the network which has impact on the loss's reduction and voltage profile

improvement with optimal sizes. The load pattern and its nature are essential for better management as they have impact on the losses and voltage profile.

Small sources with modular power technologies, ranging from 1 kW to 50 MW, are known as distributed generation. They produce electricity closer to the points of consumption. Conventional and non-conventional both types of distributed generation are available. Solar power, wind power, small hydro, natural gas generators, biogas, biomass, and geothermal power are the non-conventional types, and in conventional types of fuel cells, diesel generators, sterling engines, gas turbines, and internal combustion reciprocating engines are there [3].

Various techniques and approaches have been proposed by different authors to address the issues of optimal sizing and placement of distributed generation considering different load models and different types of DGs. The number, size, and position of multi-distributed generation (multi-DG) units in distribution networks with different load models have been chosen by authors in [4] using a multi-objective index-based Particle Swarm Optimization technique. In [5] voltage-dependent load model of the distribution system has been taken into consideration for the appropriate location and size of distributed generators. A cuckoo search algorithm-based multi-objective index-based technique was implemented in [6] to optimize the DG's size and site under various load scenarios. A soft computing technique has been proposed in [7] for the Optimal sizing and sitting of DG with considering different distribution load models. In [8] Various load models' effects on distributed generation planning are proposed by considering single and multiple DG units. The optimal positioning and size of DG units considering different load models have been addressed in [9] using a unique multi-objective quasi-oppositional grey wolf optimizer approach. The impacts of load models and load demand in the distribution system when distributed generators are present have been taken into consideration in [10]. Performance of Voltage Step Constraints and Load Models in the Optimal Location and Size of Distributed Generation, using Incremental Power Flow and the Exhaustive Search Approach, [11].

All loads that are taken into account are of constant P, Q loads during the conventional power flow analysis. This presumption is unworkable in the actual operation of a dynamic, complicated power system. Such load modeling may produce contradictory findings and erroneous conclusions, which might result in inaccurate assessments of power loss, cost, deferral values, and other system indices [12]. Loads are often modeled as voltage or frequency dependent in actual power system static or dynamic studies. Loads come in a variety of forms and classifications. Voltage-dependent loads are classified based on the ZIP model as polynomial load model and exponential load model. In the previous proposed works in literature, load models are formulated based on their types and categories as constant, residential, commercial, and industrial loads.

In this paper, the exponential load model (ZIP model) is considered and problem is formulated for the optimal allocation and sizing of DG units. Different nature-based optimization techniques have been utilized to find the optimal DG placement and sizing considering multi-objectives in the objective function. The multi-objective

function contains minimization of cost of line losses, real power generated by DG, and voltage deviation. The main contribution of the papers is:

- Improving the technical, economic, and environmental benefits by integrating different types of DGs into the distribution network.
- Three different nature-based evolutionary algorithms have been implemented and their result has been compared to get the best optimization among them.
- The lowering of DG unit generation costs, improvement of bus voltage variation, and reduction of power loss.
- To research various load models used in a real-world distribution system operation situation.
- The IEEE 85-BUS test radial distribution system was used to compare the solutions of various load models and types of DGs.

This paper is organized as follows: Sect. 2 introduces the formulation of distribution system load models. The multi-objective function formulation is done in Sect. 3. In a discussion in Sect. 4, the simulation findings for the test system are provided. Finally, the conclusions and references of the suggested work are provided.

2   Formulation of Distribution System Load Model

2.1   Exponential Load Model

The power-voltage relationship at the load bus is represented by exponential equations in the exponential model. These equations are essentially described in the ZIP model, except they contain fewer coefficients. To explain the algebraic connection between active & reactive power with applied voltage V, the exponential load model comprises two coefficients (exponents) termed n_p and n_q.

$$P = P_0 \left(\frac{\upsilon}{\upsilon_0} \right)^{n_p} \tag{1}$$

$$Q = Q_0 \left(\frac{\upsilon}{\upsilon_0} \right)^{n_q} \tag{2}$$

where P and Q are the real and reactive power of the actual load, V is the applied voltage of the load bus, V_0 is nominal voltage, P_0, Q_0 are the nominal active and nominal reactive power of the load, and n_p, n_q are exponential model coefficients.

The load behavior is expressed by the exponential models using the exponent's n_p and n_q as follows:

- Constant Impedance load (CI) when $n_p=n_q=2$
- Constant Current load (CC) when $n_p=n_q=1$
- Constant Power load (CP) when $n_p=n_q=0$

2.2 *Polynomial Load Model (ZIP)*

In practical distribution systems, the actual load is the combination of different nature of loads like constant power, constant current, and constant impedance. Such types of loads can be represented by the ZIP model, also known as the polynomial load model. In order to calculate the actual power (active power), the ZIP model adds Constant Impedance (CI), Constant Current (CC), and Constant Power (CP) to create a polynomial equation that describes the connection between the load power's characteristics and the applied voltage. Equations (3)–(4) mentioned here reflect the ZIP model algebraically:

$$P = P_0\left[a_p\left(\frac{V}{V_0}\right)^2 + b_p\left(\frac{V}{V_0}\right) + c_p\right] \tag{3}$$

$$Q = Q_0\left[a_q\left(\frac{V}{V_0}\right)^2 + b_q\left(\frac{V}{V_0}\right) + c_q\right] \tag{4}$$

where P denotes the load's real active power demand, Q denotes its actual reactive power demand, V denotes the load's actual voltage at the load bus, V_0 denotes the load's nominal voltage, P_0 denotes the load's nominal active power, and Q_0 denotes the load's nominal reactive power. The ZIP load model parameters for active power are a_p, b_p, and c_p, and a_q, b_q, and c_q are the ZIP load model coefficients for reactive power; where the values of $a_p = 0.1$, $b_p = 0.1$, $c_p = 0.8$, $a_q = 0.1$, $b_q = 0.1$, and $c_q = 0.8$.

3 Mathematical Formulation

Finding the optimal location and size of DG units considering the impact of different distribution load models to reduce the overall cost of the system while taking equality and inequality limitations into consideration is the main goal of the multi-objective problem formulated here.

3.1 Energy Loss Costs (CL)

The annual cost of power loss is given below:

$$CL = (TPRL) * (Kp + Ke * Lsf * 8760)\$ \tag{5}$$

The loss factor is presented below as a function of the load factor (Lf).

$$Lsf = k * Lf + (1 - k) * Lf^2 \tag{6}$$

where CL = annual cost of energy losses, TPRL = total real power loss of the system, LSF = loss factor, k = 0.2, Lf = 0.47, Kp = 57.6923 \$/kW, and Ke = 0.00961538 \$/kWh.

3.2 Cost of the DG for Reactive and Actual Power

$$C(P_{DG}) = \alpha * P_{DG}^2 + b * P_{DG} + c\$/MWh \tag{7}$$

The following cost coefficients are used: $\alpha = 0$, b = 20, c = 0.25

Based on the most complex power that DG can deliver, the cost of reactive power is determined as follows:

$$C(Q_{DG}) = \left[C(S_{Dg}) - C\left(\sqrt{S_{DgMAX}^2 - Q_{Dg}^2} \right) \right] * k \tag{8}$$

$$S_{DgMAX} = \frac{P_{DgMAX}}{\cos\varnothing} \tag{9}$$

To conduct the analysis, the power factor has been taken as 0.9 lagging and unity with $P_{DgMAX} = 1.1 * P_{DG}$. k is between 0.05 and 0.1, 0.1 is used in this study.

3.3 Reflection of Voltage Deviation on Cost

The distribution system voltage may change as a result of the penetration of DG units. The voltage violation should thus be kept to a minimum. The voltage deviation is described as follows.

$$V_D = \sum_{i=1}^{N_l} |V_i - V_M| \tag{10}$$

The following is the formulation of how the voltage variation impacts the cost:

$$C_{VD} = V_D W_{VD} \tag{11}$$

where V_D is the voltage deviation at load buses, $V_M = 1.0 p.u$ is the maximum allowable voltage, C_{VD} is the cost due to voltage deviation, W_{VD} is the economic operator of voltage deviation.

3.4 Multi-objective Function

$$\min F = \alpha_1 CL + \alpha_2 C(\text{P}_{\text{DG}}) + \alpha_3 C_{VD} \tag{12}$$

where F is the multi-objective function, CL is the annual cost of line loss, $C(\text{P}_{\text{DG}})$ is the total annual DG generation cost, C_{VD} is the annual voltage deviation cost, α_1, α_2, and α_3 are the weight factor of the objective function and the values are 0.786, 0.0265, and 0.1875 respectively.

The constraints are:

Voltage limits:

$$0.95 \leq V_i \leq 1.06 \tag{13}$$

Power balance limitation:

without considering DG units:

$$P_{Grid} = \sum_{j=1}^{N_l} P_d(j) + P_{loss} \tag{14}$$

$$Q_{Grid} = \sum_{j=1}^{N_l} Q_d(j) + Q_{loss} \tag{15}$$

with considering DG units

$$P_{Grid} + \sum_{i=1}^{N_{DG}} P_{DGi} = \sum_{j=1}^{N_l} P_d(j) + P_{loss} \tag{16}$$

$$Q_{Grid} + \sum_{i=1}^{N_{DG}} Q_{DGi} = \sum_{j=1}^{N_l} Q_d(j) + Q_{loss} \tag{17}$$

Upper and lower limits of DG

$$60 \text{ KW} \leq P_{DG} \leq 3500 \text{ KW} \tag{18}$$

4   Simulation Results and Discussion

Figure 1 depicts the IEEE-85 Bus standard 12.66 kV radial distribution system, which contains 85 buses and 84 branches. The one-line diagram of the IEEE test system is shown in Fig. 1. The analysis is carried out for a multi-objective function using metaheuristic technique and the results are obtained and compared with three algorithms. The total load on the system is 2.3788 MVAR and 2.661 MW, respectively are the total load on this test system bus and line data were extracted from [13]. This simulation takes into account the backward-forward sweep approach to carry out the distribution system load flow analyses. The DG's size and location are obtained for a test system at the given load scenario. The maximum iteration size taken is 100 and the population size is taken as 50. The simulation study of the test system has been carried out using MATLAB 2021a software and an Intel Core I3 10th Gen CPU with 8.0 GB of RAM. Three different optimization techniques, whale optimization from [14], grey wolf optimization from [15], and firefly algorithm from [16], are implemented for the analysis of optimal DG allocation and the results are compared to validate the above multi-objective problem formulation.

The losses, DG size, minimum voltage, maximum voltage bus, cost of emery loss are obtained for different types of loads at unity power factor is given in Table 1. Comparing the results with different techniques, the firefly algorithm has performed well in three cases and losses obtained are minimal. The voltage profile curve with different load models and different techniques at unity power factor is shown in Fig. 2. The blue line in the graph represents the base case without DG placement and the other three colors represent results with the three DG placement.
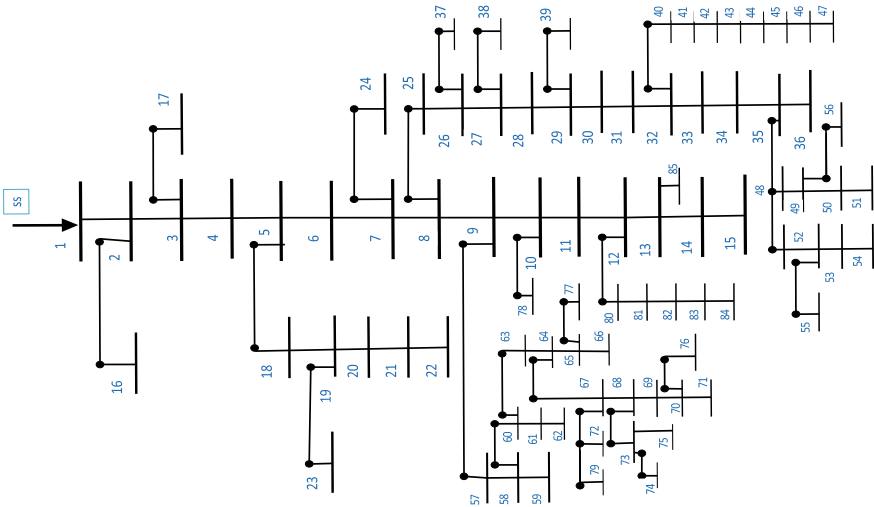

Fig. 1   One-line diagram of IEEE-85 BUS radial distribution system

Table 1 Comparison of different parameters with different algorithms at unity power factor

Parameters	Constant Power (CP)			
	Base	Whale	Gwo	Firefly
Active power loss	212.8156	142.1956	145.7648	116.6554
Reactive power loss	133.6105	81.2419	82.5248	70.1582
Number of DG	Nil	3	3	3
Optimal DG location	Nil	68/34/53	47/9/40	60/63/36
Optimal DG size P KW	Nil	794/1087/633	791/344/980	796/626/878
Optimal DG size Q Kvar	Nil	0/0/0	0/0/0	0/0/0
Minimum voltage	0.90752	0.97209	0.95566	0.96967
Minimum voltage bus number	54	84	76	84
Maximum voltage	0.9969	1.006	1.0026	0.99854
Maximum voltage bus number	2	53	47	2
Cost of line/Energy losses in $	17,130.642	11,446.0725	11,733.3756	9390.2087
Cost of Pdg ($/MWH)	Nil	50.53	42.55	46.25
Cost of Q ($/MVARH)	Nil	4.3181	3.6364	3.9524
Execution time	0.093163	165.2648	163.3334	163.6892
Parameters	Constant Current (CC)			
	Base	Whale	Gwo	Firefly
Active power loss	179.9943	120.8651	100.3181	110.6617
Reactive power loss	113.1624	69.4993	61.8868	65.1737
Number of DG	Nil	3	3	3
Optimal DG location	Nil	49/65/40	2/72/48	85/69/56
Optimal DG size P KW	Nil	1073/749/542	60/748/713	540/876/878
Optimal DG size Q Kvar	Nil	0/0/0	0/0/0	0/0/0
Minimum voltage	0.91536	0.97449	0.96078	0.97833
Minimum voltage bus number	54	84	84	43
Maximum voltage	0.99711	1.004	0.9982	0.99871
Maximum voltage bus number	2	49	2	2
Cost of line/Energy losses in $	14,488.688	9729.0668	8075.1324	8907.7369
Cost of Pdg ($/MWH)	Nil	47.53	30.67	46.13
Cost of Q ($/MVARH)	Nil	4.0618	2.6213	3.9422
Execution time	0.060565	167.5929	163.1372	164.3701
	Constant Impedance (CI)			
Active power loss	156.8548	113.2255	117.9073	107.1056
Reactive power loss	98.7214	63.9807	66.2219	61.468
Number of DG	Nil	3	3	3
Optimal DG location	Nil	84/69/48	41/31/40	31/41/76
Optimal DG size P KW	Nil	213/635/1401	997/432/268	583/755/827

Table 1 (continued)

	Constant Power (CP)			
Optimal DG size Q Kvar	Nil	0/0/0	0/0/0	0/0/0
Minimum voltage	0.9213	0.97956	0.95872	0.9752
Minimum voltage bus number	54	15	76	84
Maximum voltage	0.99728	1.0063	0.99854	0.99877
Maximum voltage bus number	2	48	41	2
Cost of line/Energy losses in $	12,626.0652	9114.113	9490.9752	8621.4891
Cost of Pdg ($/MWH)	Nil	45.23	34.19	43.55
Cost of Q ($/MVARH)	Nil	3.8653	2.9221	3.7218
Execution time	0.066352	168.8701	163.5817	163.9136
	ZIP load			
Active power loss	204.2579	132.1819	128.2455	112.2748
Reactive power loss	128.279	76.1429	79.4284	67.3835
Number of DG	Nil	3	3	3
Optimal DG location	Nil	48/60/68	32/50/27	30/35/68
Optimal DG size P KW	Nil	1399/267/802	321/590/165	627/695/898
Optimal DG size Q Kvar	Nil	0/0/0	0/0/0	0/0/0
Minimum voltage	0.9095	0.97311	0.94091	0.96951
Minimum voltage bus number	54	84	76	84
Maximum voltage	0.99695	1.0004	0.99776	0.99855
Maximum voltage bus number	2	48	2	2
Cost of line/energy losses in $	16,441.7856	10,640.0121	10,323.1502	9037.5894
Cost of Pdg ($/MWH)	Nil	49.61	21.77	44.65
Cost of Q($/MVARH)	Nil	4.2395	1.8605	3.8158
Execution time	0.071562	166.0708	163.2554	163.4411

The optimal DG placement and sizing problem may have a solution with higher sizes of DG units, for power loss reduction, but the cost of DG allocation would rise. Therefore, in order to conduct a realistic feasibility analysis of DG installation at a site, it is required to examine various aspects of cost, power loss, and voltage enhancement at the same time taking a multi-objective case. Maximum three DGs are taken into consideration in this study to obtain the best location and size for DGs. It is observed from Table 1, that grey wolf optimization algorithm gives the lowest DG power generation cost.
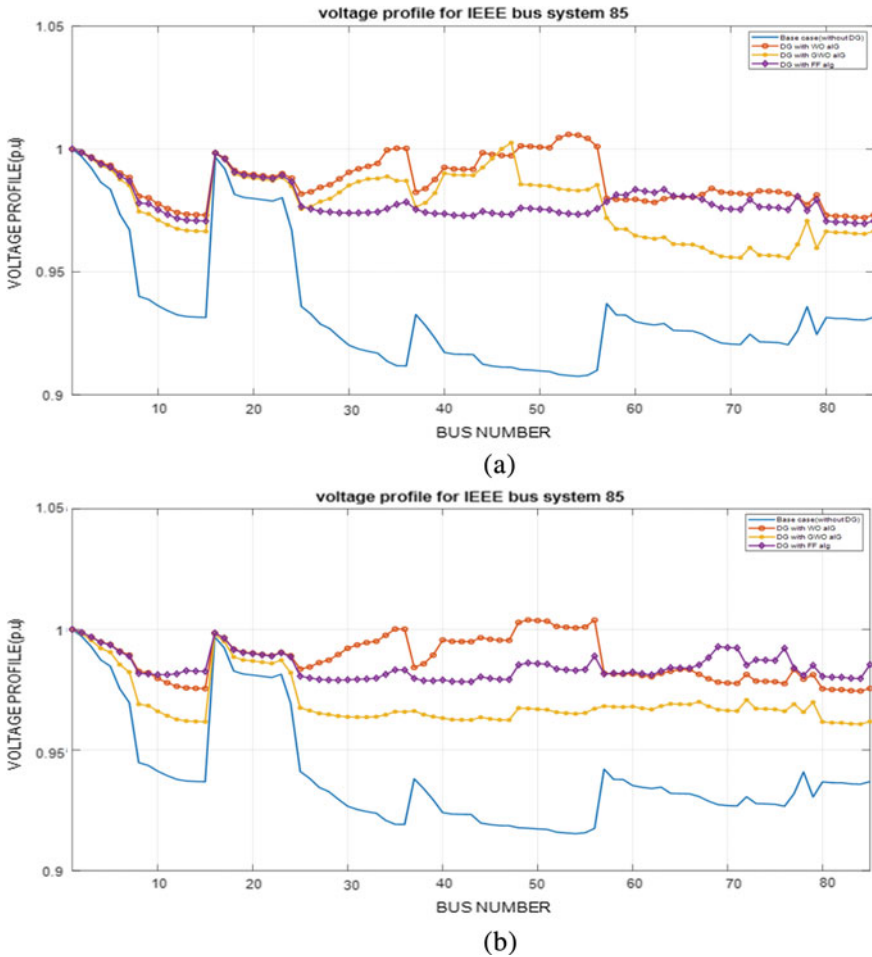
(a)

(b)

Fig. 2 Voltage profiles for various load models in an 85-BUS system with three DG operating at unity power factor **a** Constant Power (CP) **b** Constant Current (CC) **c** Constant Impedance (CI) **d** ZIP load

In Table 2, the results are obtained with three DG at 0.9 lagging power factor case and are tabulated. The lowest annual line loss cost is obtained with firefly algorithm and the lowest DG generation cost is obtained with Grey Wolf Optimization algorithm. The improved voltage profile curve with 0.9 lagging power factor for different distribution load models taking different heuristic techniques is presented in Fig. 3. The voltage profile is better with DGs for all the cases of loads.

Fig. 2 (continued)

(c)

(d)
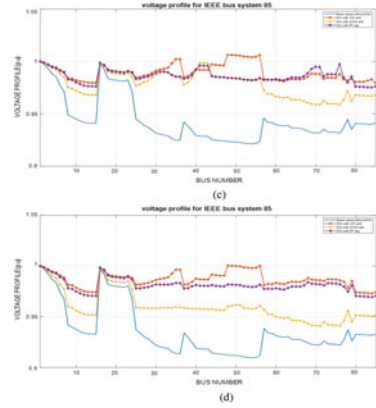
5 Conclusions

This paper presented three different metaheuristic optimization algorithms for optimal DG allocation and sizing considering the effect of different distribution load models. Exponential and polynomial load model of distribution system has been considered in this study. The results of various approaches presented in the paper have been compared for different types of load models. The formulation of a MOF with several different objectives, DG annual generation cost, annual cost of power loss, and voltage deviation cost are determined. Investigations of the results with different load models and their effect on voltage profile are presented. The results have been compared with different algorithms at varying power factor. Whale Optimization, Grey Wolf Optimization, and Firefly Algorithms are compared to loss reduction and DG cost. IEEE-85 BUS radial distribution system has been taken as a case study to validate the above scenarios. Future research can take into account the shifting demand profile taking demand response program and its impact on the operation and management considering the EVs load and storage devices.

Table 2 Comparison of different parameters with different algorithms at 0.9 lag power factor

	Constant Power (CP)			
Parameters	Base	Whale	Gwo	Firefly
Active power loss	212.8156	66.3423	79.6937	65.3305
Reactive power loss	133.6105	32.9205	44.7748	33.1067
Number of DG	Nil	3	3	3
Optimal DG location	Nil	43/68/52	11/12/35	54/72/56
Optimal DG size P KW	Nil	621/809/1082	60/60/1388	887/873/481
Optimal DG size Q Kvar	Nil	300/391/524	29/29/672	429/422/232
Minimum voltage	0.90752	0.9871	0.95542	0.9815
Minimum voltage bus number	54	84	76	84
Maximum voltage	0.9969	1.035	0.99854	1.0304
Maximum voltage bus number	2	52	35	54
Cost of line/Energy losses in $	17,130.642	5340.2395	6414.9643	5258.7928
Cost of Pdg ($/MWH)	Nil	50.49	30.41	45.07
Cost of Q ($/MVARH)	Nil	4.9038	2.9528	4.3772
Execution time	0.14696	167.3439	165.2409	163.4633
	Constant Current (CC)			
Parameters	Base	Whale	Gwo	Firefly
Active power loss	179.9943	64.4497	51.52	44.8128
Reactive power loss	113.1624	31.0324	29.2536	23.3105
Number of DG	Nil	3	3	3
Optimal DG location	Nil	69/85/56	33/24/11	51/33/58
Optimal DG size P KW	Nil	749/189/1414	1196/60/367	725/715/882
Optimal DG size Q Kvar	Nil	362/91/684	579/29/177	351/346/427
Minimum voltage	0.91536	0.99091	0.96321	0.98657
Minimum voltage bus number	54	84	76	76
Maximum voltage	0.99711	1.0344	0.99869	1.0224
Maximum voltage bus number	2	56	2	51
Cost of line/Energy losses in $	14,488.688	5187.8935	4147.114	3607.2193
Cost of Pdg ($/MWH)	Nil	47.29	32.71	46.69
Cost of Q ($/MVARH)	Nil	4.5929	3.1763	4.5346
Execution time	0.083512	166.4707	165.3276	168.0667
	Constant Impedance (CI)			
Parameters	156.8548	53.3583	54.7656	36.5692
Active power loss	98.7214	26.3495	28.2068	19.3764
Reactive power loss	Nil	3	3	3
Number of DG	Nil	34/79/55	30/52/11	63/61/48
Optimal DG location	Nil	1412/608/229	1653/90/60	869/481/864
Optimal DG size P KW	Nil	683/294/110	800/43/29	420/232/418

Table 2 (continued)

|	Constant Power (CP)			
Optimal DG size Q Kvar	0.9213	0.98948	0.97141	0.98975
Minimum voltage	54	84	76	84
Minimum voltage bus number	0.99728	1.0278	1.0075	1.0083
Maximum voltage	2	55	30	48
Maximum voltage bus number	12,626.0652	4295.0924	4408.3728	2943.6476
Cost of line/Energy losses in $	Nil	45.23	36.31	44.53
Cost of Pdg ($/MWH)	Nil	4.3928	3.5261	4.3248
Cost of Q ($/MVARH)	0.12053	169.7483	167.7229	167.5108
Execution time	0.12053	169.7483	167.7229	167.5108
	ZIP load			
Parameters	204.2579	49.2881	109.1829	62.8579
Active power loss	128.279	25.0413	52.928	31.4008
Reactive power loss	Nil	3	3	3
Number of DG	Nil	36/84/79	49/4/21	54/77/50
Optimal DG location	Nil	1357/375/736	1885/60/80	607/914/821
Optimal DG size P KW	Nil	657/181/356	912/29/38	293/ 442/397
Optimal DG size Q Kvar	0.9095	0.99233	0.96494	0.98505
Minimum voltage	54	22	76	84
Minimum voltage bus number	0.99695	1.021	1.0342	1.032
Maximum voltage	2	36	49	54
Maximum voltage bus number	16,441.7856	3967.4539	8788.7008	5059.7585
Cost of line/Energy losses in $	Nil	49.61	40.75	47.09
Cost of Pdg ($/MWH)	Nil	4.8183	3.9575	4.5735
Cost of Q ($/MVARH)	0.10908	168.2883	168.3482	167.3802
Execution time	0.10908	168.2883	168.3482	167.3802
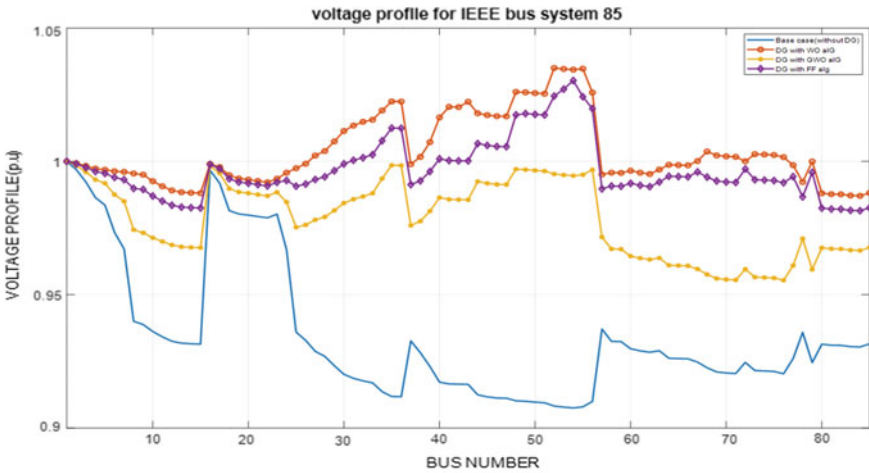
(a)
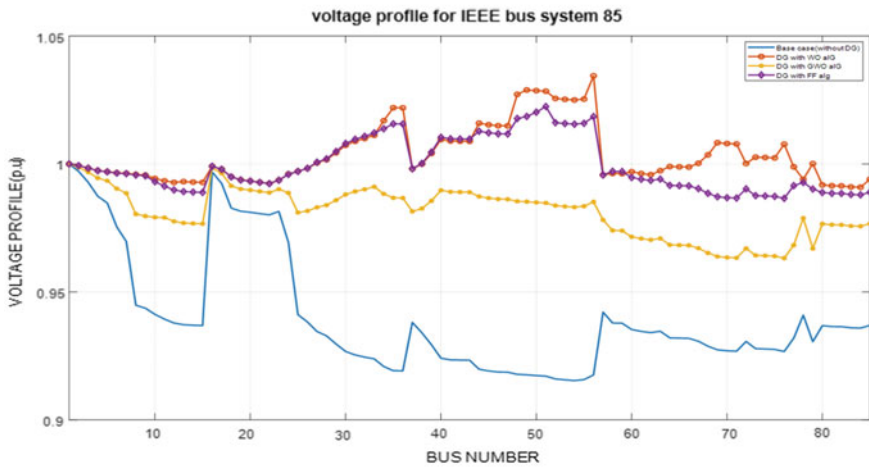
(b)

Fig. 3 Voltage profiles of 85-BUS system with three DG at 0.9 lagging power factor for different types of load models **a** Constant Power (CP) **b** Constant Current (CC) **c** Constant Impedance (CI) **d** ZIP load
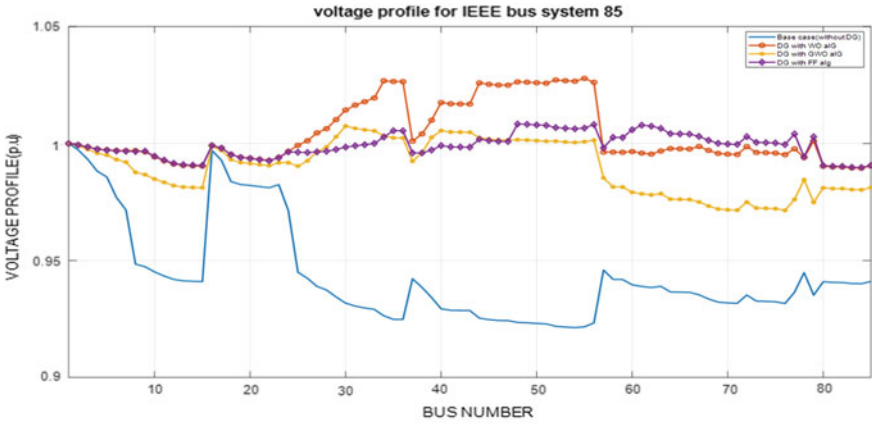
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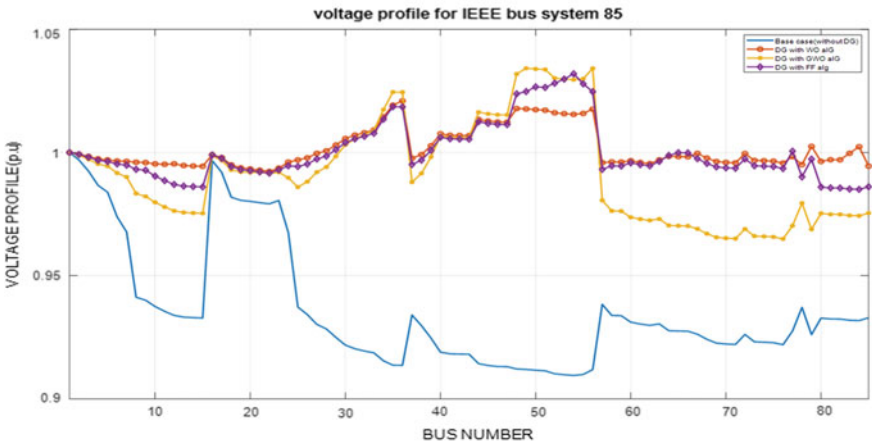
(d)

Fig. 3 (continued)

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