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Multi-Objective Optimization Approach for Placement of Multiple DGs for Voltage Sensitive Loads

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Abstract: This paper presents the optimal placement of multiple Dispersed Generators using multi-objective optimization. The optimization is carried out with objectives namely active power loss, reactive power loss, voltage deviation and overall economy. The multi-objective optimization and accounting conflicting objectives are realized through Particle Swarm Optimization with fuzzy decision approach to find the optimal sizes and sites of Dispersed Generators for voltage dependent residential, commercial and industrial loads. The clusters of buses are formulated from base case load flow to limit the search space for finding the placement of the Dispersed Generators. The effectiveness of the proposed approach is tested on a 69-bus radial distribution. It is found that the optimal placement of the Dispersed Generators improves the overall performance of the system and the optimal allocation is affected by the type of load.

Keywords: Dispersed Generator (DG); fuzzy membership function; multiple DG; multi-objective optimization; optimal size and site

1. Introduction

The distribution system is the final interconnection between the bulk power system and consumers. There is a large number of buses and lines with a high R/X ratio, which results into high power losses in distribution systems. These losses are even more significant at heavy loads. Moreover, the voltage of buses, farther from the substation, decreases. It is important to optimize the operation of distribution systems by reducing the losses and enhancing the voltages profile. To assure these improvements reconfiguration and capacitor placement have been employed earlier but in recent decade the placement of dispersed generation has attracted the researchers. Dispersed Generators (DGs) are small-scale generators that are located near to load centers. The size of DGs varies from less than a kW to tens of MW. The DGs have additional advantage of meeting load demand along with reduction in losses and improvement of voltage profile. To maximize these benefits, DG of optimal size should be placed at optimal site. Several optimization techniques have been utilized for DG placement by optimizing various objective functions, as single objective and multi-objective optimization problem.

The placement of DG as single objective optimization is carried out through various optimization techniques for loss minimization, cost minimization, profit maximization. These methods include Particle Swarm Optimization (PSO) [1,2], Genetic Algorithm (GA) [3], Artificial Bee Colony (ABC) [4], Improved Bat Algorithm [5], and Analytical expression based heuristics [6–9]. The limitation of analytical expression based heuristics is inability to handle multiple objectives and multiple DGs.

The optimal placement of DG has been investigated through PSO [1,2] to minimize losses in distribution system. The effectiveness of three different types of DGs have been analyzed [1]. The DG that is capable of supplying both active and reactive power is most effective for loss reduction. Loss minimization has been investigated by integrating multiple DGs [2]. The realistic nature of loads has been accounted by time-varying characteristics. GA [3] has been applied to optimally allocate DGs to minimize losses. It has been concluded that the benefit of loss minimization by DG placement is limited up to certain locations only and after that trend reverses. The problem of DG placement to minimize losses has been solved by ABC algorithm [4] for two different load scenarios. Multiple DG placement has been obtained by Bat Algorithm [5] to achieve maximum reduction in annual energy losses in distribution system.

An analytical heuristic based on exact loss formula has been derived to attain the optimal size and location of DG [6] to reduce the power losses in distribution system. The location of DG, capable of supplying only active power, is found by sensitivity loss factors. The heuristic proposed in [6] is elaborated to consider different types of DG [7]. Another classical technique utilizes loss formula based on bus-injection to branch-current (BIBC) and branch-current to bus-voltage (BCBV) matrices [8] to calculate the optimal size and site of DG. This method does not require calculation of impedance matrix. Another technique based on analytical expressions [9] obtain the optimal site and size of four different types of DG by minimizing the losses. A decision making approach [10] based on exhaustive load flow has been employed to allocate wind and photovoltaic (PV) based DGs in distribution system to reduce the power losses and improve voltage profile. The PV based DG is found more influential in voltage profile improvement in comparison to wind based DG.

The multi-objective optimization problem has been solved by two different approaches i.e., by representing multi-objective optimization as single objective optimization using weighed sum approach or by handling multiple objectives simultaneously. The common objectives for multi-objective DG placement are minimization of power loss, voltage deviation, customer interruptions, cost of purchased energy and cost of DG.

The weighted sum approach has been used in [11–15] to find the optimal size and optimal site of DG. The allocation has been investigated through GA [11] where the multi-objective problem is changed to single objective by assigning weights to four objectives namely real and reactive power loss index, voltage profile index and Mega Volt Ampere (MVA) capacity index. In addition to these four objectives short-circuit current is also considered as objective in [12]. The optimization has been carried out using PSO after changing the multi-objective problem to single objective problem. Optimal site of DG for predefined size has been obtained by Simulated Annealing [13] for minimizing power loss, emissions and contingency. Optimal allocation of multiple DGs based on wind turbine and PV array has been done by PSO [14] for minimizing power loss and improving voltage stability. The multi-objective optimization problem is converted to single objective by assigning weights, where the weights were updated iteratively. Weighted sum approach has also been utilized in [15] for optimal sizing and siting of voltage controlled DG for balanced as well as unbalanced distribution networks for objectives as real and reactive power loss index, voltage profile index and reserve capacity of conductor index. The optimization has been attempted by supervised big-bang crunch method. The limitation of weighted sum approach is that the solution is dependent on weight assigned to each objective or the decision maker who assigns the weights to the objectives, influences the solution. Such solutions may be non-optimal solutions.

Multi-objective optimization problem has been solved by ε-constrained technique in [16–18] to suggest optimal allocation of DG in which one objective is selected as main objective and rest of objectives are treated as constraints. Minimization of cost of energy losses, voltage profile and power quality index are selected as objectives in [16] to attempt optimization by ε-constrained technique. The ε-constrained technique has been combined with GA [17] for optimal allocation of DG by minimizing four costs network upgrading, purchased energy, energy losses, energy not supplied. The combination of ε-constrained technique and GA [18] has been employed to allocate DG optimally considering voltage dependent loads. The minimization of interruptions to customers, cost of active power losses, cost of energy purchased, bus voltage deviation and maximization of security margin has been considered as multiple objectives.

Optimal location and size of DG has been obtained by Strength Pareto Evolutionary Algorithm and Non-dominated Sorting GA-II in [19] and Shuffled frog leaping algorithm in [20] to minimize real power loss and cost of DG. Optimization of weight factor is additional parameter to be optimized in [20] which balances the two main objectives. In addition to minimization of real power losses of system and cost of DG, voltage deviation minimization is also considered as objective in [21]. Non-dominated Sorting GA-II was used to solve the problem of optimal allocation of specified number of DGs of multiple types. The pareto front is obtained for simultaneous optimization of three objectives and final solution is selected from non-dominated solutions by normalized membership functions. Optimal allocation of DG models has been done by minimizing voltage deviation index, real and reactive power loss index, line loading index and short-circuit index using fuzzy embedded GA [22]. The multi-objective problem is simplified by assigning fuzzy membership function to each index. Goal optimization algorithm [23] has been used for optimal allocation of DG in distribution system by achieving the set goal for the indices used in [22]. In [24] combination of GA and PSO has been utilized by where optimal site is obtained by GA and size of DG is obtained by PSO. Multiple DGs of optimal size has been placed to minimize losses, improve voltage profile and to optimize voltage stability index. Enhanced multi-objective PSO has been proposed to optimally allocate multiple DGs by minimizing power losses and maximize voltage stability index [25,26]. Fuzzy decision-making has been employed to select single solution from Pareto front. Sequential quadratic programming has been employed in [27] to obtain set of optimal solutions to minimize total real power loss and cost of DG. In addition to loss and voltage deviation minimization, cost minimization is also considered as objective [28]. Shuffled Bat algorithm has been employed in solving optimization. Pareto front has been obtained in both and compromised solution has been selected from set of solutions. The best solution has been selected by fuzzy decision-making in [27] and while it has been done by max-min technique in [28].

The GA and PSO are commonly used techniques for optimal placement of DG. The PSO has better diversity and exploration in comparison to GA and its convergence is fast due to momentum effect on particles [29]. Therefore, the optimization in the presented work is carried out through PSO.

In this paper the four indices are selected for allocation of DG of optimal size at optimum location in radial distribution system (RDS). These indices are active power loss index (PLI), reactive power loss index (QLI), voltage deviation index (VDI) and overall economy index (OEI). The multi-objective optimization is implemented using fuzzy decision approach by assigning fuzzy memberships to these indices and optimizing the resultant membership. The optimal sizes and sites of DGs are obtained through PSO for voltage dependent residential, commercial and industrial loads. The optimization is carried out for placement of single as well as multiple DGs. The clustering of buses based on base case load flow is done to reduce the search space.

2. Objectives for DG Placement

The placement of DG in RDSs affects active power losses, reactive power losses and, voltage profile of buses. If DG of appropriate size is placed at optimum site then the losses will decrease and voltage profile of the buses gets improved. In the presented work four individual objectives are accounted simultaneously for the multi-objective formulation. Corresponding to these objectives, the values of indices before placement of DG is taken as unity and it is desired to reduce the value of these indices by placement of optimal sized DG at optimal site. These indices are formulated as:

2.1. Active Power Loss Index (PLI)

With the integration of DG in RDSs, active power losses are expected to reduce. The active power loss index (PLI) gives the effectiveness of DG integration on active power loss and is defined as:

$$PLI = \frac{P_L^{DG}}{P_L} \tag{1}$$

This objective attempts to minimize active power loss in distribution system by addition of DG.

2.2. Reactive Power Loss Index (QLI)

The reactive power loss also varies with integration of DG in RDSs. The effectiveness of DG integration on reactive power losses is given by QLI, which is defined as:

$$QLI = \frac{Q_L^{DG}}{Q_L} \tag{2}$$

This objective minimizes reactive power loss in distribution system by addition of DG.

2.3. Voltage Deviation Index (VDI)

The voltage deviation (VD) is a measure of the deviation of bus voltages from reference bus. The effectiveness of improvement in voltage profile of buses after optimal placement of DG is measured by voltage deviation index (VDI). It is defined as:

$$VDI = \frac{VD^{DG}}{VD} \tag{3}$$

where VD^{DG} and VD are measure of deviation in the bus voltage with respect to reference voltage after and before integration of DG respectively. These are defined as:

$$VD^{DG} = \sum_{i=2}^{n} \left(\frac{V_{nom} - V_i^{DG}}{V_{nom}} \right)^2$$

$$VD = \sum_{i=2}^{n} \left(\frac{V_{nom} - V_i}{V_{nom}} \right)^2$$

2.4. Overall Economy Index (OEI)

Economy is accompanying every activity in today's competitive market. The overall economy index (OEI) is minimized so as to make DG operation economical. The *OEI* is expressed as:

$$OEI = \frac{CE^{DG}}{CE} \tag{4}$$

CE^{DG} and CE are stated as:

$$CE^{DG} = P_L^{DG} C_{PT} + \sum_{i=1}^{n} \left(C_{PT} (P_i^D - P_i^{DG}) + C^{DG} P_i^{DG} \right) \tag{5}$$

$$CE = P_L C_{PT} + \sum_{i=1}^{n} \left(C_{PT} P_i^D \right)$$

3. Multi-Objective Planning for DG Placement

A general multi-objective problem can be formulated mathematically as:

$$\min f(X) = \{f_1(X), f_2(X), f_3(X), \ldots\ldots\ldots\ldots\ldots\ldots f_n(X)\} \tag{6}$$

Subjected to

$$h(X) = 0$$

$$C(X) \leq 0$$

Such that

$$X \in S$$

where X is solution vector, S is solution space, $f_i(X)$ is ith objective function, $h(X)$ is equality constraint and $C(X)$ is inequality constraint.

The objectives in the multi-objective optimization are usually conflicting. The objectives that are optimized simultaneously are expressed through indices namely PLI, QLI, VDI and OEI. Instead of using the true Pareto based optimization, the objectives are combined using the membership functions derived from the fuzzy decision approach. The fuzzy membership function values (μ) are computed for each objective and are defined as:

$$\begin{gathered} \mu_j = 0, \text{ for } y_j \leq y_1; \\ \mu_j = \frac{(y_j - y_1)}{(y_2 - y_1)}, \text{ for } y_1 < y_j < y_2; \\ \mu_j = 1, \text{ for } y_j \geq y_2 \end{gathered} \tag{7}$$

where y_j is the value of performance index.

In this presented work the values of y_2 and y_1 are considered as 1.25 and 0 respectively.

The multi-objective function (MOF) formulated by combining four objectives functions can be expressed as:

$$\min MOF = \min\{(\mu_{PLI} \times PLI) + (\mu_{QLI} \times QLI) + (\mu_{VDI} \times VDI) + (\mu_{OEI} \times OEI)\} \tag{8}$$

where μ_y is the fuzzy membership assigned to index y.

The objective function represented by Equation (8) is subjected to inequality constraints of bus voltage limits and MVA capacity of lines.

3.1. Bus Voltage Constraints

The incorporation of DGs in RDS boosts the voltage level of all buses, which may result in over-voltage at some buses. Moreover, there are always limits on lower level of voltage so the bus voltage constraints are defined as:

$$V_i^{\min} \leq V_i \leq V_i^{\max}$$

The limits for $V_i^{\min}$ and $V_i^{\max}$ are taken as 0.90 and 1.05 p.u. [30].

3.2. MVA Capacity Constraints

The integration of DG in RDS changes the nature of RDS from passive to active and hence the current levels change. This constraint is necessary to ensure thermal limits of lines. MVA capacity constraint is expressed as:

$$S_{ij} \leq S_{ij}^{\max}$$

3.3. Limiting Search Space

The search space for optimal allocation of DG is limited by making the clusters of buses. Bus voltages obtained after the load flow for the base case are used to decide these clusters. These clusters represent the group of buses having significant low voltage. The potential buses for the placement of DGs are selected from the cluster of buses, and thus limiting the search space. Such identified cluster of buses although reduces the search space but always yields optimal solution and thereby does not compromise on the quality of the optimal solution.

4. Voltage Dependent Loads

The effect of node voltage on connected load is accounted while evaluating the optimal site and size of DG for single as well as multi-objective optimization. The practical loads such as industrial, commercial, residential are prevalent in the RDS. These practical loads affect the bus voltage or bus voltages affect the power drawn by these loads. These loads are modeled as:

$$P_i = P_{i0} V_i^{np}$$

$$Q_i = Q_{i0} V_i^{nq}$$

Here *np* and *nq* are the active and reactive power exponents. These exponents are considered as zero for constant load, which is conventionally, used in power flow studies. The value of these exponents for various types of loads is tabulated in Table 1 [18].

Table 1. Load models and exponents [18].

Load	*np*	*nq*
Constant	0	0
Commercial	1.51	3.40
Residential	0.92	4.04
Industrial	0.18	6.00

5. Algorithm for DGs Allocation

PSO is a population-based search and optimization technique in which individuals called particles change their position (state) with time. In PSO, particles move through the search space to keep itself in the best position *pbest*. The best position searched by the group particles *gbest* is assessable to each particle. The particles change their position with the help of their current positions, their *pbest* and *gbest*. The Figure 1 shows the flowchart for implementing the multi-objective DG allocation problem using PSO, where algorithm steps are described as follows:

Step 1 Read the distribution system line and bus data and the type of load.

Step 2 Carryout the base case load flow using Bus injection to branch current (BIBC) and branch current to bus voltage (BCBV) matrices [31].

Step 3 Calculate the indices i.e., PLI, QLI, VDI and OEI before placement of DG.

Step 4 Identify the cluster of buses for obtaining optimal site of DG.

Step 6 Initialize the particles positions that are random DGs at random buses in the search space and set the iteration counter $k = 0$.

Step 6 For these positions, calculate load flow and check for constraints satisfaction. Compute the performance indices and corresponding membership functions using Equation (7).

Step 7 Obtain the objective function from Equation (8).

Step 8 For the positions, assign them as individual best positions *pbest*. Also identify the best of the *pbest* as global best *gbest*.

Step 9 Update the particles positions by accounting their adaptive weight and current positions [1], *pbest* and *gbest* and increase iterations as $k = k + 1$.

Step 10 Go to Step 6 until the convergence is achieved.

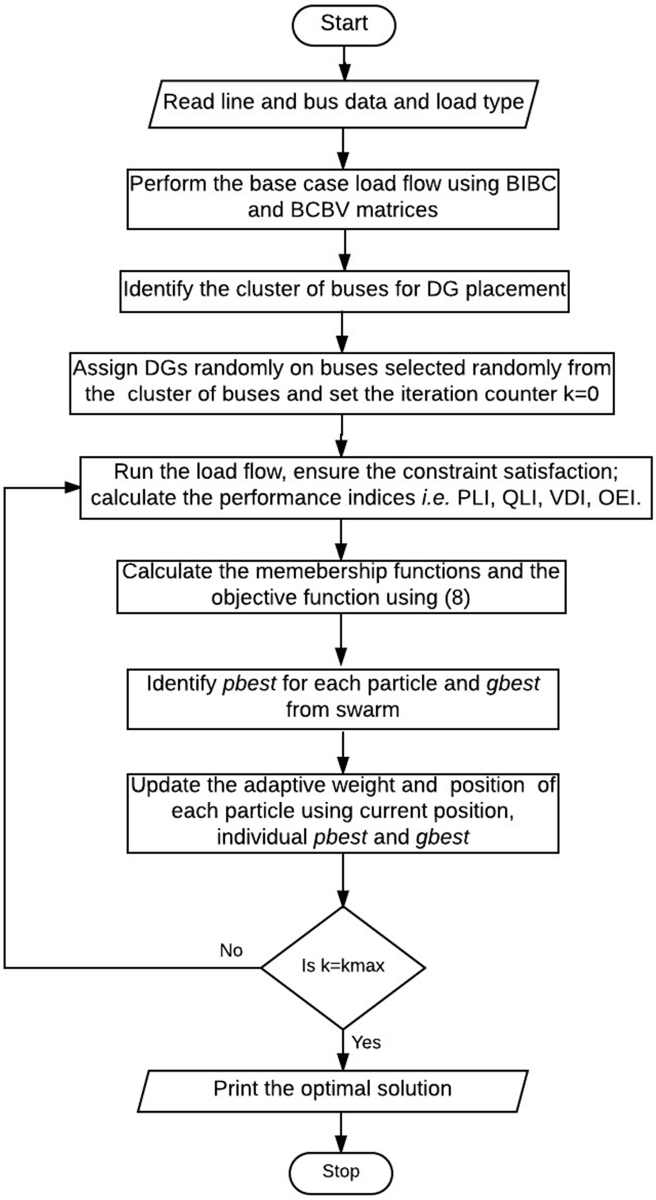

Figure 1. Flowchart for the proposed DG allocation technique.

6. Results

The methodology adopted for optimal allocation of DG in this presented work is tested on IEEE 69-bus RDS [32]. This system has total load of 3.800 MW and 2.690 MVAr and it is resulting into 225.005 kW active power losses and 102.173 kVAr reactive power losses. The algorithm is implemented under MATLAB (R2014b, MathWorks, Natick, MA, USA) in MAC environment. The presented algorithm has been executed while considering the swarm size as 50 for 50 iterations. For multi-objective optimization the optimal size and site of DG are found for the placement of single as well as multiple DGs. The DGs that are capable of supplying only active power, is considered for optimization.

The search space for obtaining optimal site of DG is obtained by forming the clusters of buses with significantly lower bus voltage from base-case load flow for all types of loads. The variation of bus voltage for base case is shown in Figure 2. Two clusters of buses with minimum voltage are selected to obtain the optimal site of DG. First cluster of buses consists of buses from 57 to 65 and second cluster of buses ranges from bus 16 to 28.

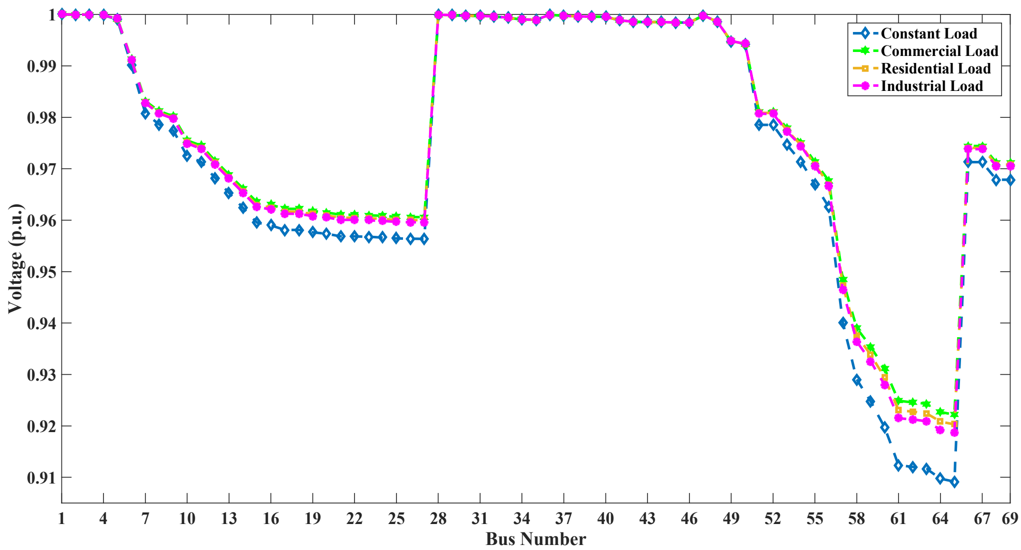

Figure 2. Variation of base-case bus voltage for all loads.

6.1. DG Placement Using Single Objective Optimization

Optimal size and site of DG are found when all four indices are considered independently for placement of single as well as multiple DGs. For placement of single DG, only first cluster of buses is considered while for placement of two DGs, one DG is selected from each of the respective cluster. The four cases that are investigated for DG placement through single objective optimization are: Minimizing PLI, Minimizing QLI, Minimizing VDI and Optimizing OEI.

6.1.1. Minimizing PLI

With PLI as objective, the optimal size and site of DG and corresponding indices after optimal allocation of DG for all types of loads are presented in Table 2. The value of PLI is 1.0 before placement of DG in RDS. Its value reduces significantly after integration of optimal sized DG at optimal site due to reduction in active power loss. For constant load the improvement is maximum, where its value reduces to 0.3696 and 0.3280 corresponding to placement of single and multiple DGs respectively. The values of all other indices also reduce after placement of DG.

Table 2. Optimal size and site of DG and Indices values for power loss index (PLI) as objective.

Type of Load	Optimal DG Size (MW)	Optimal DG Site	PLI	QLI	VDI	OEI
Constant	1.88	61	0.3696	0.3964	0.2011	0.4946
	1.83, 0.42	61, 26	0.3280	0.3596	0.0689	0.4641
Commercial	1.63	61	0.4437	0.4763	0.2805	0.5839
	1.37, 0.46	61, 23	0.3962	0.4366	0.1527	0.5485
Residential	1.62	61	0.4217	0.4555	0.2790	0.5646
	1.51, 0.34	61, 26	0.3763	0.4166	0.1502	0.5307
Industrial	1.70	61	0.3893	0.4235	0.2533	0.5388
	1.62, 0.50	61, 21	0.3352	0.3762	0.0893	0.4985

6.1.2. Minimizing QLI

With QLI minimization, the resulted optimal DG size, site and corresponding values of indices are presented in Table 3 for placement of single as well as multiple DGs. In addition to reduction in QLI all other indices also reduces i.e., performance is improved. The reduction in QLI is almost same for both objectives PLI and QLI as both are dependent on current.

Table 3. Optimal size and site of DG and Indices values for reactive power loss index (QLI) as objective.

Type of Load	Optimal DG Size (MW)	Optimal DG Site	PLI	QLI	VDI	OEI
Constant	1.9252	61	0.3700	0.3961	0.1920	0.4974
	1.80, 0.57	61, 19	0.3199	0.3522	0.0519	0.4578
Commercial	1.76	61	0.4461	0.4764	0.2512	0.5864
	1.34, 0.57	62, 23	0.4054	0.4432	0.1313	0.5558
Residential	1.76	61	0.4239	0.4522	0.2473	0.5668
	1.61, 0.54	61, 22	0.3682	0.4068	0.0852	0.5256
Industrial	1.70	61	0.3891	0.4234	0.2549	0.5386
	1.64, 0.52	61, 25	0.3475	0.3849	0.0799	0.5080

6.1.3. Minimizing VDI

The deviation in bus voltages in RDS is an important factor, which can be improved by integration of DG. The optimal size, site of DG and performance indices are summarized in Table 4 corresponding to minimization of VDI for placement of single as well as multiple DGs. The size of DG for VDI optimization is higher in comparison to the sizes of DGs obtained for optimizing PLI and QLI independently. The improvement in VDI results in improvement of voltage of all buses in RDS. The placement of multiple DGs is found more effective as the reduction in VDI is more as compared to single DG placement.

Table 4. Optimal size and site of DG and Indices values for voltage deviation index (VDI) as objective.

Type of Load	Optimal DG Size (MW)	Optimal DG Site	PLI	QLI	VDI	OEI
Constant	2.98	58	0.5706	0.5622	0.1016	0.6603
	2.33, 0.69	63, 20	0.4033	0.4289	0.0057	0.5260
Commercial	2.54	59	0.6173	0.6169	0.1527	0.7177
	2.33, 0.71	62, 19	0.5273	0.5471	0.0068	0.6522
Residential	2.67	59	0.6277	0.6232	0.1376	0.7238
	2.41, 0.65	60, 21	0.5325	0.5537	0.0083	0.6528
Industrial	2.82	58	0.6523	0.6387	0.1265	0.7415
	2.35, 0.71	63, 20	0.5274	0.5495	0.0069	0.6470

6.1.4. Optimizing OEI

The optimization of overall economy index OEI is very important objective as economy is major decision factor. For OEI formulation, the cost of power supplied by DG is taken as 46 US$/MWh and power tariff is taken as 44.5 US$/MWh [18]. Corresponding to the optimization of OEI, the optimal placement and values of the indices are summarized in Table 5. The reduced value of OEI results in economic operation of DG. It is observed that placement of multiple DGs is more economical as compared to single DG. The obtained OEI for placement of two DG is always lower than its value for single DG. The reduction in OEI follows the pattern of PLI, as OEI is dependent on active power losses given by Equation (5).

Table 5. Optimal size and site of DG and Indices values for OEI as objective.

Type of Load	Optimal DG Size (MW)	Optimal DG Site	PLI	QLI	VDI	OEI
Constant	1.87 1.78, 0.50	61 61, 20	0.3696 0.3197	0.3966 0.3529	0.2030 0.0640	0.4696 0.4576
Commercial	1.55 1.52, 0.54	61 62, 25	0.4452 0.4076	0.4790 0.4431	0.2996 0.0969	0.5848 0.5581
Residential	1.60 1.58, 0.49	61 61, 23	0.4219 0.3675	0.4558 0.4070	0.2815 0.0999	0.5647 0.5247
Industrial	1.63 1.66, 0.45	61 61, 22	0.3879 0.3362	0.4232 0.3775	0.2685 0.0924	0.5376 0.4993

The size of DG is higher for constant load model among four types of loads for every objective and hence the reduction in all objectives is also maximum for constant load model.

6.2. DG Placement Using Multi-Objective Optimization

The placement of DG using multi-objective optimization is discussed for two cases. In first case PLI and VDI are considered simultaneously and in second case all the four objectives (PLI, QLI, VDI and OEI) are considered simultaneously.

6.2.1. Validation of Proposed Technique

The results obtained from proposed PSO based technique are compared with multi-objective GA for validation. The comparison of DG size, site and performance indices obtained by proposed technique with GA for single objective as well as multi-objective case is presented in Table 6. In addition to multi-objective case the comparison of two techniques is also done for single objective case. The constant load model is considered for comparison and is equally applicable to other load models.

Table 6. Validation of proposed technique.

Objective	Method	Optimal DG Size (MW)	Optimal DG Site	PLI	QLI	VDI	OEI
PLI	PSO	1.87	61	0.3696	0.3964	0.2011	0.4949
	GA	1.87	61	0.3696	0.3964	0.2011	0.4949
	PSO	1.83, 0.42	61, 26	0.3280	0.3596	0.0689	0.4641
	GA	1.82, 0.42	61, 26	0.3280	0.3596	0.0692	0.4641
VDI	PSO	2.98	58	0.5703	0.5619	0.1017	0.6600
	GA	2.98	58	0.5703	0.5619	0.1017	0.6600
	PSO	2.33, 0.69	63, 20	0.4033	0.4289	0.0057	0.5260
	GA	2.34, 0.70	63, 20	0.4065	0.4317	0.0057	0.5286
Both PLI and VDI	PSO	2.09	61	0.3766	0.3997	0.1666	0.5029
	GA	2.09	61	0.3766	0.3997	0.1666	0.5029
	PSO	1.91, 0.48	61, 26	0.3312	0.3609	0.0477	0.4669
	GA	1.91, 0.48	61, 26	0.3312	0.3609	0.0477	0.4669

The optimal sizes of DG for the placement of single as well as multiple DGs obtained by both techniques are comparable. In implementation of GA true Pareto front is obtained while in PSO fuzzy memberships are assigned that yields in fast convergence. The true Pareto front for the placement of single DG as well as multiple DGs is shown in Figures 3 and 4 respectively.

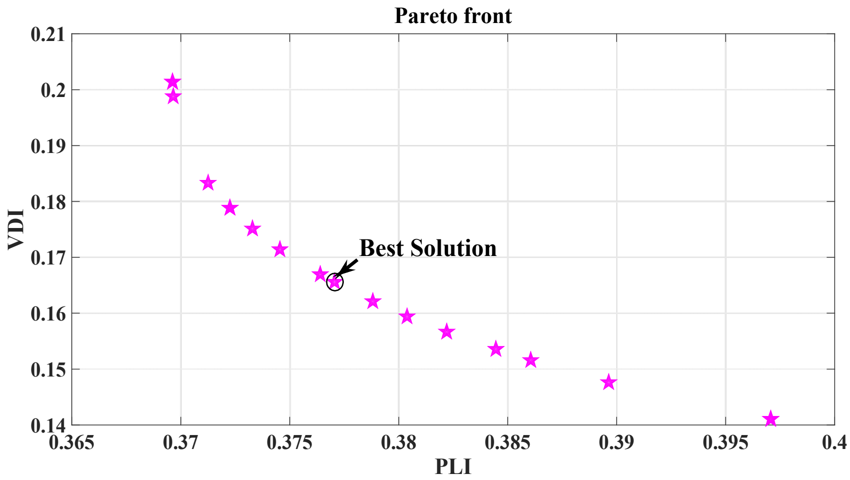

Figure 3. Pareto front for the placement of single DG.

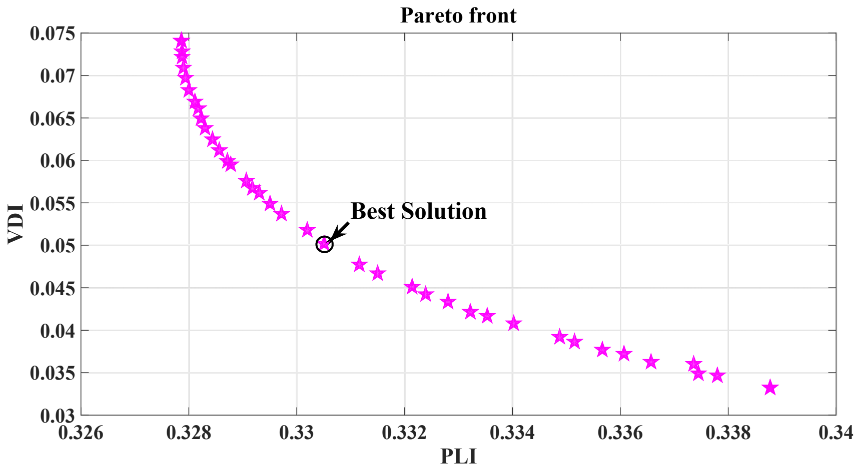

Figure 4. Pareto front for the placement of multiple DG.

6.2.2. Case I Optimizing both PLI and VDI Simultaneously

The placement of single as well as multiple DGs has been investigated by considering PLI and VDI simultaneously by assigning fuzzy membership function to each performance index. For all types of voltage dependent loads optimal size, site and corresponding value of each index after placement of DGs are summarized in Table 7.

Table 7. Optimal size and site of DG for the placement of single DG and multiple DG and Indices values for multi-objective optimization (PLI and VDI).

Type of Load	Optimal DG Size (MW)	Optimal DG Site	PLI	QLI	VDI	OEI
Constant	1.87	61	0.3696	0.3966	0.2030	0.4696
	1.78, 0.50	61, 20	0.3197	0.3529	0.0640	0.4576
Commercial	1.55	61	0.4452	0.4790	0.2996	0.5848
	1.52, 0.54	62, 25	0.4076	0.4431	0.0969	0.5581
Residential	1.60	61	0.4219	0.4558	0.2815	0.5647
	1.58, 0.49	61, 23	0.3675	0.4070	0.0999	0.5247
Industrial	1.63	61	0.3879	0.4232	0.2685	0.5376
	1.66, 0.45	61, 22	0.3362	0.3775	0.0924	0.4993

These results are compared to the single objective optimization results presented in Tables 2 and 4, which summarize the results corresponding to minimization of PLI and minimization of VDI respectively. From Tables 2 and 4, it is clear that the value of PLI is minimum, while VDI is maximum when only PLI is the objective, whereas VDI is minimum and PLI is maximum when only VDI is the objective for all types of loads.

The results of multi-objective optimization, while compared with single objective optimization, PLI and VDI forms the non-dominated set of solutions. The variation of PLI with variation in VDI for placement of single as well as multiple DGs is shown in Figure 5a–d for different types of load models. From the Pareto front, a set of optimal solutions obtained by multi-objective optimization, the best compromised solution is obtained. The compromised solutions are marked as encircled solutions while; the extreme solutions are for individual objectives. As the optimal solution set corresponding to the multiple DG placement is more dominant i.e. near to the origin, which suggests that the placement of multiple DGs is more beneficial and multiple DG placement reduces values of indices as compared to single DG placement.

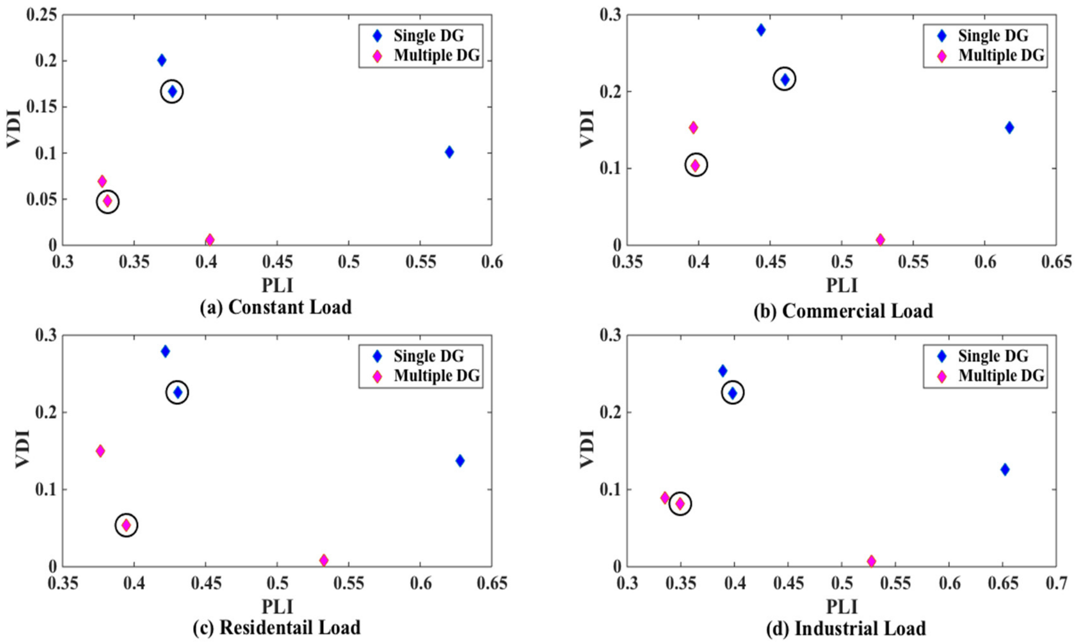

Figure 5. Variation of PLI with variation in VDI for placement single and multiple DGs. (**a**) constant load; (**b**) commercial load; (**c**) residential load; (**d**) industrial load.

6.2.3. Case-II Optimizing All Indices Simultaneously

In second case of multi-objective optimization based placement of DG, all four indices PLI, QLI, VDI and OEI are combined by assigning fuzzy membership to each index. The optimal size and site of DG and all indices are tabulated in Table 8. It is observed from results that type of load is affecting DG size and site significantly.

The placement of multiple DGs is more advantageous as compared to single DG placement and it results in reduced values of indices. The reduced values of PLI and QLI show reduction in active and reactive power losses respectively and reduced values of VDI show improvement in voltage profile of all buses. The reduction in OEI means that integration of DG in distribution system is economical as it reduces the losses and cost of DG is being overcome by reduction in losses.

Table 8. Optimal size and site of DG for single and multiple DG placement and Indices values for multi-objective optimization (all objectives).

Type of Load	Optimal DG Size (MW)	Optimal DG Site	PLI	QLI	VDI	OEI
Constant	1.97 1.85, 0.48	61 61, 27	0.3712 0.3308	0.3964 0.3608	0.1838 0.0546	0.4984 0.4665
Commercial	1.92 1.80, 0.74	61 61, 20	0.4580 0.4181	0.4845 0.4477	0.2197 0.0372	0.5961 0.5680
Residential	1.91 1.85, 0.49	61 61, 19	0.4355 0.3802	0.4631 0.4168	0.2166 0.0600	0.5761 0.5354
Industrial	1.86 1.85, 0.41	61 61, 22	0.4000 0.3521	0.4306 0.3906	0.2216 0.0741	0.5473 0.5117

6.3. Bus Voltage after DG Placement

The placement of DGs of optimal size at optimal site improves the voltage of all buses of the RDS. The variation of voltage of each bus after and before placement of optimal sized DG at optimal site for multi-objective optimization after considering all indices is shown in Figures 6–9 for four different types of loads. The plot of voltage indicates that the improvement in bus voltage is better with placement of multiple DGs as compared to single DG. Also the voltage of all buses is within the limits of voltage constraints for all types of load after placement of single as well as multiple DG.

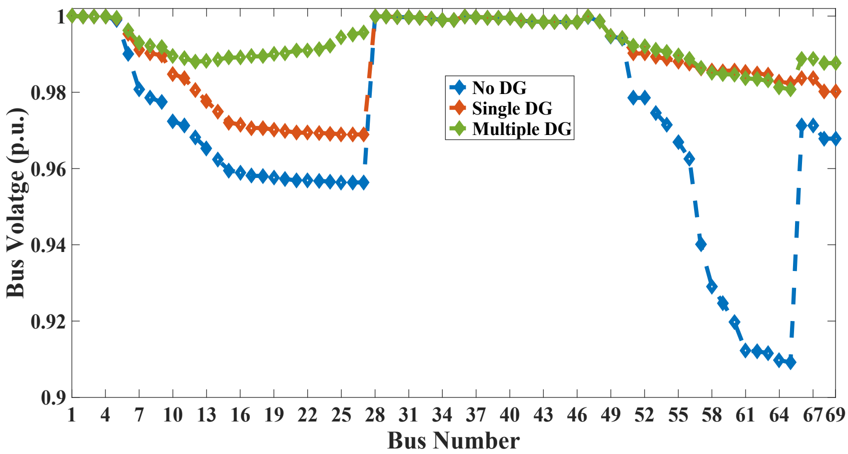

Figure 6. Variation of bus voltage before and after placement of DG for Constant Load.

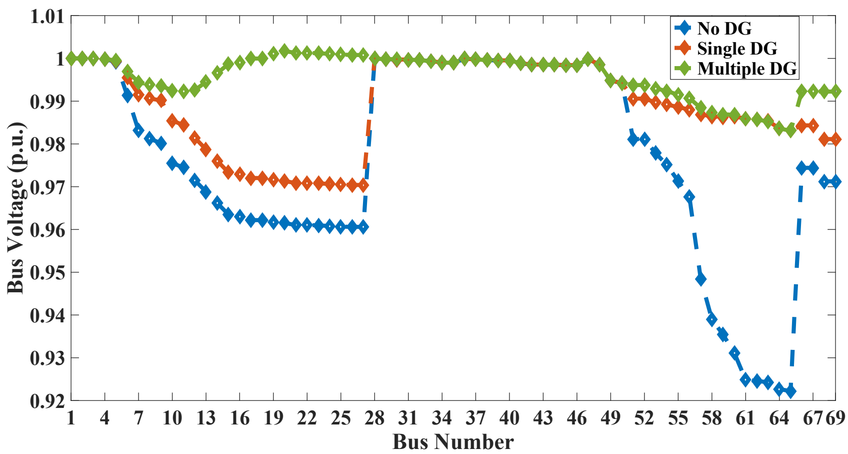

Figure 7. Variation of bus voltage before and after placement of DG for Commercial Load.

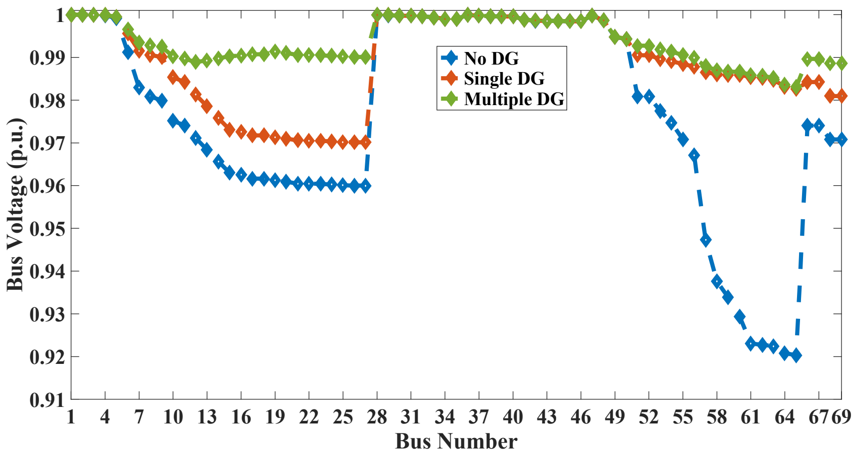

Figure 8. Variation of bus voltage before and after placement of DG for Residential Load.

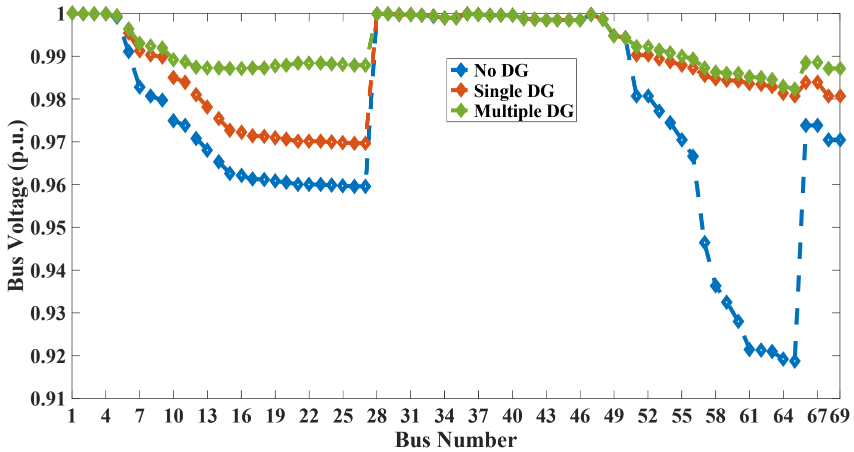

Figure 9. Variation of bus voltage before and after placement of DG for Industrial Load.

The effect of selection of DG on voltage profile of all buses is shown in Figure 10 for constant load model. Significant improvement in voltage of all buses is achieved after optimal integration of DG corresponding to all individual objectives and two cases of multi-objective optimization but it is maximum for placement of multiple DGs corresponding to objective VDI.

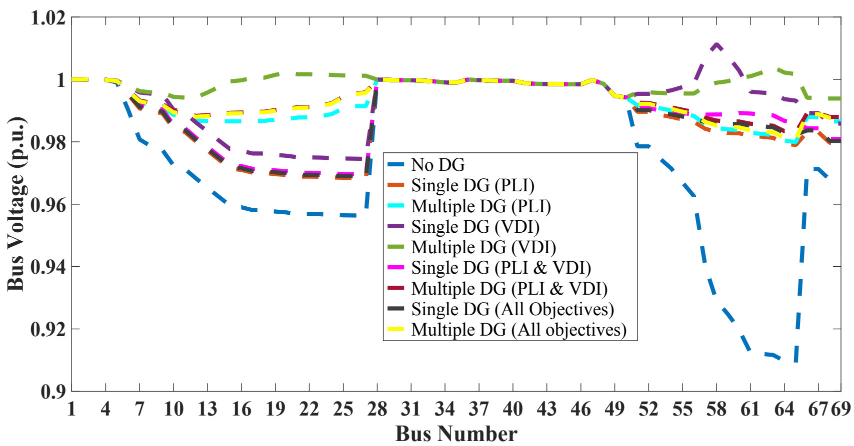

Figure 10. Variation of bus voltage showing effect of objective for constant load.

6.4. Comparative Results

The proposed technique is validated by comparing with well-known multi-objective GA as presented in Table 6. Further the obtained results are compared with the available results in literature for placement of single as well as multiple DGs. The comparative analysis is presented in Table 9.

Table 9. Comparative results.

Objective	Number of DG	Method	DG Size (MW) @ Site	% Loss Reduction
Loss Reduction	1	PSO [1]	1.81 @ 61	62.95
		GA [3]	1.87 @ 61	63.01
		ABC [4]	1.90 @ 61	62.97
		Analytical [6]	1.81 @ 61	62.86
		Analytical [8]	1.81 @ 61	59.09
		Analytical [9]	1.81 @ 61	62.97
		Proposed Method	**1.88 @ 61**	**63.04**
	2	GA [3]	1.78 @ 61, 0.56 @ 11	68.09
		Proposed Method	**1.80 @ 61, 0.57 @ 19**	**68.10**

7. Discussion

The optimal placement of single as well as multiple DGs has been investigated for voltage sensitive loads through the optimization of objectives represented through indices PLI, QLI, VDI and OEI. The single and multi-objective optimization has been investigated for the placement of single DG and placement of multiple DGs. As summarized in Section 6.1 through Tables 2–5, the values of PLI, QLI, VDI and OEI through single objective optimization are higher for single DG placement then the respective values obtained with the placement of two DGs. This suggests that the placement of two DGs is yielding better optimization. The comparative results have been included in Table 9, where the results of proposed method have been compared with published results obtained through various heuristics PSO [1], GA [3], ABC [4], and Analytical methods [6,8,9] for minimizing losses. The proposed method is giving better performance. The multi-objective optimization, as summarized in Section 6.2 through Tables 7 and 8, yields the lower values of indices with two DG placement in comparison to single DG placement. The Pareto-front as shown in Figure 5 is closer to origin for two DG. This suggests that two DG placement is yielding better optimization compared to single DG placement. With multiple DGs of optimum size, the compensation is affected at multiple locations and thereby the load burden is not getting reflected up to substation. Such multiple DG placement thereby resulting into reduced losses, improved bus voltage profile. The ideal numbers of DG placement is an area of research and beyond the scope of presented manuscript.

8. Conclusions

In this paper a fuzzy decision based multi-objective optimization approach is presented to decide the optimal placement of single and multiple DGs. The optimization problem is solved by PSO to yield optimal solution. The search space for selection of optimal sites for DG placement is reduced by forming the cluster of buses. The proposed approach is implemented on 69-bus RDS for different voltage sensitive residential, commercial and industrial loads. It is observed that the load types significantly affects the sites and sizes of DGs. The significant improvement in the voltage profile is observed at all buses after integration of DG of optimal size at optimal site. Moreover, the placement of multiple DGs is found to be more effective in improving the system performance as compared to placement of single DG. Two DGs are sufficient to improve the overall performance for both single and multi-objective optimization for different loads.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

CE and CE^{DG}	Cost of losses and energy purchased before and after integration of DG respectively
C_{PT}	Power tariff
C^{DG}	Cost of power supplied by DG
n	Number of buses
P_i^{DG}	Power supplied by *i*th DG
P_i^D	Load demand at *i*th bus
P_i and Q_i	Active and reactive power at *i*th bus
P_{i0} and Q_{i0}	Actual active are reactive power at *i*th bus
P_L and P_L^{DG}	Active power loss before and after integration of DG respectively
Q_L and Q_L^{DG}	Reactive power loss before and after integration of DG respectively
S_{ij} and $S_{ij}^{\max}$	MVA flow in line between bus i and j and maximum limit of S_{ij}
VD and VD^{DG}	Deviation in the bus voltage before and after integration of DG respectively
V_i and V_i^{DG}	Voltage of *i*th bus before and after placement of DG respectively
$V_i^{\min}$	Minimum level of the voltage of *i*th bus
$V_i^{\max}$	Maximum level of the voltage of *i*th bus
V_{nom}	Nominal voltage (V_{nom} = 1 p.u.)

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