

Hybrid Approach for Placement of Multiple DGs in Primary Distribution Networks

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Abstract - This paper proposes the hybrid approach for multiple distributed generators placement to achieve a high loss reduction in a primary distribution networks. The analytical method has been extended for practical power injections. This approach is based on improved analytical expressions to calculate the optimum size of DGs and heuristic technique to identify the best locations for DG allocations. The optimal power factors of the DGs have also been evaluated in this work. To validate the proposed hybrid approach, results have been compared with particle swarm optimization (PSO) technique and existing fast improved analytical (IA) approach results. The proposed technique has been tested on 33-bus test system.

Keywords: Analytical Expressions, Distributed Generation, Particle Swarm Optimization (PSO), Optimal Size, Optimal Location, Power Loss

I. INTRODUCTION

The global concerns about the environment, combined with the progress of technologies to connect renewable energy sources to the grid and deregulation of electric power market have diverted the attention of distribution system planners towards grid-connected distributed generation (DG). Most of the DG energy sources are designed using green energy which is assumed pollution free [1]. The technical benefits include improvement of voltage, loss reduction, relieved transmission and distribution congestion, improved utility system reliability and power quality. All these benefits are achieved by installing DG at proper location with proper size. Several methods have been reported for optimal siting and sizing of the DG through different optimization technique improving technical and economical performances [2-5].

Including DG in distribution systems requires in-depth analysis and planning tools. This process usually includes technical, economical, regulatory, and possibly environmental challenges. Some of the factors that must be taken into account in the planning process for the expansion of distribution system with DG are: the number and capacity of DG units, best locations and technology, the network connection, capacity of existing system, protection schemes, among others. Different methodologies and tools have been developed to identify optimal places to install DG capacity. These methodologies are based on analytical tools, optimization programs or heuristic techniques. Most of them determine the optimal allocation and size of single DG

[7, 11-15], in order to reduce losses and improve voltage profile with various techniques. Others include the placement of multiple DGs [9, 16-20], with artificial intelligence-based optimization methods and a few go with analytical approach.

In [4], a GA based method was proposed to find the optimal placement of DG in the compensated distribution network for restoration the system caused by cold load pick up (CLPU) condition and to conserve load diversity for reduction in losses, improvement in voltage regulation. In [5], a mixed integer linear program was formulated to solve the optimization problem. The objective was to optimally determine the DG plant mix on a network section. In [6-8], a particle swarm optimization (PSO) algorithm was introduced to determine the optimum size and location of a single DG unit to minimize the real power losses of the system. The problem was formulated as one of constrained mixed integer nonlinear programming, with the location being discrete and the size being continuous. However, the real power loss of the system was the only aspect considered in this work. In [9], different scenarios were suggested for optimum distribution planning. One of these scenarios was to place multiple DG units at certain locations pre-determined by the Electric Utility Distribution Companies aiming to improve their profiles and minimize the investment risk. In [10], the objective was to minimize a multi-objective performance index function using GA. The indices were reflecting the effect of DG allocation on the real and reactive power losses of the system, the voltage profile, and the distribution line loading with different load models. In [11], an analytical method to determine the optimum location-size pair of a DG unit was proposed in order to minimize the line losses of the power system.

For placing multiple DG units, many research papers have been presented. In [13], a GA-based algorithm was used to determine the optimum size and location of multiple DG units to minimize the system losses and the power supplied by the main grid, taking voltage constraint at each node of the system into consideration. In [14], DG units were placed at the most sensitive buses to voltage collapse. The units had the same capacity and were placed one by one. In [15, 16], a GA-based algorithm was presented to locate multiple DG units to minimize a cost function including the system losses and service interruption costs. In [17], an adaptive-

weight PSO algorithm was used to place multiple DG units, but the objective was to minimize only the real power loss of the system. A probabilistic-based planning technique was proposed for determining the optimal fuel mix of different types of renewable DG units in order to minimize the annual energy losses in the distribution system [18]; however, DG units capable of delivering real power only is considered in this work.

Many researchers have applied artificial intelligence-based optimization methods for finding the best locations for the placement of single or multiple DGs to reduce losses. All the mentioned research placed DG units with unity power factor. Recently, a fast analytical approach to find the optimal size of DG at optimal power factor to minimize the power loss for only Type-III has been exploited [12] and another analytical multiple DG placements one by one has been presented in [19].

In fact, four types of DG are considered based on their terminal characteristics as follows

1. Type-I: DG capable of injecting real power only,
2. Type-II: DG capable of injecting reactive power only,
3. Type-III: DG capable of injecting both real and reactive power,
4. Type-IV: DG capable of injecting real but consuming reactive power.

Most of the research presented so far model the optimal placement of single DG with analytical or heuristic approach, and multiple DGs with heuristic approaches at unity power factor only. However optimal placement of multiple DGs at optimal power factors with hybrid approach being integrated into distribution systems. The present work develops the comprehensive formula by improving the analytical expression presented in [19] to find the optimal size of multiple DGs supplying real and reactive power and a PSO technique to identify best locations and optimal power factors to achieve the objective by compensating the active and reactive powers. Besides, voltage profile enhancement is also examined and the results of the proposed hybrid approach are verified with PSO technique and analytical method results.

II. MATHEMATICAL BACKGROUND

A. Sizing at Various Locations

Assuming $a_{k_i} = (sign) \tan(\cos^{-1}[PF_{DG_{k_i}}])$, the reactive power output of DG, where k_i is the bus number of i^{th} DG. $i=1, 2, 3, \dots, n$, where n is the number of DGs to be placed. Therefore,

$$Q_{DG_{k_i}} = a_{k_i} P_{DG_{k_i}} \quad \dots (1)$$

In which

$$sign = \begin{cases} +1: DG \text{ injecting Reactive Power} \\ -1: DG \text{ consuming Reactive power} \end{cases}$$

$PF_{DG_{k_i}}$ is the power factor of DG at k_i^{th} bus of i^{th} DG. The active and reactive power injected at bus k_i , where DG is located, are given by (2) and (3), respectively,

$$P_{k_i} = P_{DG_{k_i}} - P_{D_{k_i}} \quad \dots (2)$$

$$Q_{k_i} = Q_{DG_{k_i}} - Q_{D_{k_i}} = a_{k_i} P_{DG_{k_i}} - Q_{D_{k_i}} \quad \dots (3)$$

Substituting (2) and (3), the power loss equation is written as

$$P_L = \sum_{i=1}^N \sum_{j=1}^N \left[\alpha_{ij} \left((P_{DG_{k_i}} - P_{D_{k_i}}) P_j + (a_{k_i} P_{DG_{k_i}} - Q_{D_{k_i}}) Q_j \right) + \beta_{ij} \left((a_{k_i} P_{DG_{k_i}} - Q_{D_{k_i}}) P_j - (P_{DG_{k_i}} - P_{D_{k_i}}) Q_j \right) \right] \quad \dots (4)$$

Differentiating P_L w.r.t. $P_{DG_{k_1}}$

$$A_{k_1 k_1} P_{DG_{k_1}} + A_{k_2 k_1} P_{DG_{k_2}} + \dots + A_{k_i k_1} P_{DG_{k_i}} + \dots + A_{k_n k_1} P_{DG_{k_n}} = B_{k_1}$$

Differentiating P_L w.r.t. $P_{DG_{k_2}}$

$$A_{k_1 k_2} P_{DG_{k_1}} + A_{k_2 k_2} P_{DG_{k_2}} + \dots + A_{k_i k_2} P_{DG_{k_i}} + \dots + A_{k_n k_2} P_{DG_{k_n}} = B_{k_2}$$

Similarly Differentiating P_L w.r.t. $P_{DG_{k_i}}$

$$A_{k_1 k_i} P_{DG_{k_1}} + A_{k_2 k_i} P_{DG_{k_2}} + \dots + A_{k_i k_i} P_{DG_{k_i}} + \dots + A_{k_n k_i} P_{DG_{k_n}} = B_{k_i}$$

There will be n equations with n variables. These equations can be written as

$$[P_{DG}]_{n \times 1} [A]_{n \times n}^{-1} [B]_{n \times 1} \quad \dots (5)$$

Where,

$$[P_{DG}]_{n \times 1} = [P_{DG_{k_1}} \quad \dots \quad P_{DG_{k_i}} \quad \dots \quad P_{DG_{k_n}}]^T$$

$$A_{k_i k_j} = \begin{cases} \alpha_{k_i k_i} (1 + a_{k_i}^2) & \text{if } k_i = k_j \\ \alpha_{k_i k_j} (1 + a_{k_i} a_{k_j}) + \beta_{k_i k_j} (a_{k_i} - a_{k_j}) & \text{if } k_i \neq k_j \end{cases}$$

$$B_{k_i} = \begin{pmatrix} \alpha_{k_i k_i} (P_{D_{k_i}} + a_{k_i} Q_{D_{k_i}}) \\ + \sum_{\substack{j=1 \\ j \neq i \text{ (in } k_i)}}^n \left(\alpha_{k_i k_j} (P_{D_{k_j}} + a_{k_i} Q_{D_{k_j}}) - \beta_{k_i k_j} (Q_{D_{k_j}} - a_{k_i} P_{D_{k_j}}) \right) \\ + \sum_{j=1}^N \left(\alpha_{k_i k_j} (P_{D_{k_j}} + a_{k_i} Q_{D_{k_j}}) - \beta_{k_i k_j} (Q_{D_{k_j}} - a_{k_i} P_{D_{k_j}}) \right) \end{pmatrix}$$

The proposed method for calculating optimum sizes is Multivariable Optimization technique. From (5) the optimal sizes of multiple DGs at each bus can be calculated for the losses to be minimum.

B. Selecting Optimal Locations and Power Factor

For single DG placement, the number of combinations of buses possible is the total number of buses in the system. So it was simple to calculate DG size and to evaluate the loss at every bus. But when it comes to determine combination of N buses in the same network for n DGs the number of combinations possible are ${}^N C_n$ where, n is number of DGs and N is number of buses in the network. So a search technique or a heuristic method needs to be implemented to

find optimal location. The optimal location for the placement of multiple DGs is determined by using PSO technique taking the location as the variable and optimal power factor of each optimal DG is also calculated by PSO technique taking the p.f. as the another variable.

III. PROBLEM FORMULATION

A. Objective Function

The objective is to minimize the total real power loss while meeting the following constraints.

$$\text{Min } P_L = \sum_{i=1}^N \sum_{j=1}^N [\alpha_{ij}(P_i P_j + Q_i Q_j) + \beta_{ij}(Q_i P_j - P_i Q_j)]$$

- For each bus, the following power flow equations must be satisfied.

$$P_{Gi} - P_{Di} = \sum_{j=1}^N V_i V_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)] \quad \forall i = 1, 2, 3, \dots, N \quad \dots (6)$$

$$Q_{Gi} - Q_{Di} = \sum_{j=1}^N V_i V_j [G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)] \quad \forall i = 1, 2, 3, \dots, N \quad \dots (7)$$

- The voltage at every bus in the network should be within the acceptable range.

$$V_{min} \leq V_i \leq V_{max} \quad \forall_i \in \{\text{buses of the network}\} \quad \dots (8)$$

- Current in a feeder or conductor, must be well within the maximum thermal capacity of the conductor

$$I_i \leq I_i^{Rated} \quad \forall_i \in \{\text{branches of the network}\}, \quad \dots (9)$$

Here, I_i^{Rated} is current permissible for branch i within safe limit of temperature.

B. Computational Procedure

Two approaches have been used for determining the optimal sizes and locations of multiple DGs, and are given step by step in the following subsections. The backward sweep and forward sweep method of distribution load flow [22] is carried out to fulfill the desired objective.

1. Particle Swarm Optimization Technique

Particle swarm optimization (PSO) is a population-based optimization technique which provides a population-based search procedure in which individuals called particles change their position (state) with time. In a PSO system, particles fly around in an n -dimensional search space. During flight, each particle adjusts its position according to its own experience (This value is called $pbest$), and according to the experience of a neighboring particle (This

value is called $gbest$), made use of the best position encountered by itself and its neighbor [23].

Mathematically, the position i^{th} of particle in an n -dimensional vector is represented as:

$$X_i = (x_{i,1}, x_{i,2}, x_{i,3}, \dots, \dots, x_{i,n})$$

In the present work the numbers of particles are taken as 10 and the dimension of search space is 4. The current position can be modified by the following equation:

$$S_{id}^{k+1} = S_{id}^k + v_{id}^{k+1}, \quad i = 1, 2, \dots, n, \quad \dots (10)$$

$$d = 1, 2, \dots, m$$

Where,

S^k – current position of particle;
 S^{k+1} – modified position of particle.

The velocity of i^{th} particle is also represented by an n -dimensional vector,

$$V_i = (v_{i,1}, v_{i,2}, v_{i,3}, \dots, \dots, v_{i,n})$$

Velocity of each agent can be modified by the following equation:

$$v_{id}^{k+1} = \omega v_{id}^k + c_1 rand \times (pbest_{id} - s_{id}^k) + c_2 rand \times (gbest_{id} - s_{id}^k) \quad \dots (11)$$

The following weight function is used:

$$\omega_i = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{k_{max}} \cdot k \quad \dots (12)$$

Where,

ω_{min} and ω_{max} are the minimum and maximum weights respectively. k and k_{max} are the current iteration and maximum number of iterations. Appropriate values for c_1 and c_2 lies in the range 1 to 2. For fast convergence of the PSO algorithm, values of c_1, c_2, ω_{min} and ω_{max} have been selected by hit and trial approach [24], and the final values are considered as: $c_1 = c_2 = 2, \omega_{min} = 0.4$ and $\omega_{max} = 0.9$.

The exact loss formula has been taken as fitness function for PSO algorithm. The best position related to the lowest value of the objective function for each particle is

$Pbest_m = (pbest_{m,1}, pbest_{m,2}, pbest_{m,3}, \dots, pbest_{m,n})$, and the global best position among all the particles or best $pbest$ is denoted as:

$$Gbest_m = (gbest_{m,1}, gbest_{m,2}, gbest_{m,3}, \dots, gbest_{m,n}),$$

During the iteration procedure, the velocity and position of the particles are updated. The population size of swarms and iterations are fixed i.e., the PSO parameters, population size of swarms and iterations are taken 50 and 200 respectively. The position and velocity of the i^{th} particle has been considered as X_i and V_i respectively. Randomly generates an initial population (array) of particles with random positions and velocities on dimensions (Size of type-I and type-II DG, Location of type-I and type-II DG) in the solution space. For each particle, scale the sizes of type-I and type-II DG to their limits.

2. Hybrid Approach

The proposed hybrid approach has been developed to determine the optimal sizes and locations of multiple type-III DGs, and is given step by step in the following.

Step 1: Input line and bus data, and bus voltage limits.

Step 2: Calculate the loss using distribution load flow.

Step 3: Randomly generates an initial population (array) of particles with random positions and velocities on dimensions (Location of DGs and p.f of DGs) in the solution space. Set the iteration counter $k = 0$.

Step 4: For each particle, calculate the sizes of DGs using (5).

Step 5: If the bus voltage is within the limits as given, evaluate the total loss. Otherwise, that particle is infeasible.

Step 5: For each particle, compare its objective value with the individual best. If the objective value is lower than P_{best} , set this value as the current P_{best} , and record the corresponding particle position.

Step 6: Choose the particle associated with the minimum individual best P_{best} of all particles, and set the value of this P_{best} as the current overall best G_{best} .

Step 7: Update the weight, velocity and position of particle using (12), (11) and (10) respectively.

Step 8: If the iteration number reaches the maximum limit, go to Step 9. Otherwise, set iteration index $k = k + 1$, and go back to Step 4.

Step 9: Print out the optimal solution to the target problem. The best position includes the optimal locations and size of DG and the corresponding fitness value representing the minimum total real power loss.

3. Particle Swarm Optimization (PSO) Approach

The computational procedure to allocate multiple DG in the distribution system at optimal locations by PSO approach taking the constraints into consideration to minimize the power loss is described in detail as below.

Step 1: Input line and bus data, and constraints.

Step 2: Calculate the base case loss using distribution load flow based on backward sweep-forward sweep method.

Step 3: Randomly generates an initial population (array) of particles with random positions and velocities on dimensions (locations of DGs and sizes of DGs) in the solution space. Set the iteration counter $k = 0$.

Step 4: For each particle, check all the constraints are satisfy.

Step 5: If the constraints are within the limits as given, evaluate the total loss. Otherwise, that particle is infeasible so set it to base case loss.

Step 6: For each particle, compare its objective value with the individual best, if the objective value is lower than P_{best} , set this value as the current P_{best} , and record the corresponding particle position.

Step 7: Choose the particle associated with the minimum individual best P_{best} of all particles, and set the value of this P_{best} as the current overall best G_{best} .

Step 8: Update the position and velocity of particle using (10) and (11) respectively.

Step 9: If the iteration number reaches the maximum limit, go to Step 10. Otherwise, set iteration index $k = k + 1$, and go back to Step 4.

Step 10: Print out the optimal solution to the target problem. The best position includes the optimal locations and sizes of DGs and the corresponding fitness value representing the minimum total real power loss.

IV. NUMERICAL RESULTS

A. Test Systems

The proposed methodology as described in section 2 & 3 is tested on 33-bus radial distribution system with total load of 3.72 MW and 2.3 MVar [25]. An analytical software tool has been developed in MATLAB environment for both, the proposed hybrid approach and the PSO technique to run load flow, calculate losses and optimal sizes of different types of multiple DGs. The maximum number of DG units installed is assumed to be three and the total capacity of the DG units is equal to the total load plus line losses.

B. Results

1. Type-III DG Placement

Based on the result obtained, Table I presents the optimal sizes and locations at optimal power factors of DG units by the proposed hybrid approach and PSO technique. The results of the base case and DG numbers ranging from one to three are compared. For single DG, the loss reduction by hybrid approach, at 67.82% is the same as that by PSO technique. For two DG units, the loss reduction is 86.44%, which is same in both cases. For three DG units, hybrid achieves a loss reduction of 94.45%, compared with PSO technique at 94.41%. In general, the results obtained with proposed approach are nearly same as compared with PSO technique. In all the three cases the optimal locations remain same in both the techniques.

The results obtained from both the approaches are also compared with the fast improved analytical method [19] results. For 1 DG placement the reduction in line losses from all the three approaches are same but the size of DG is higher by IA method. For 2 DG placement the reduction in line losses by the IA [19] method are 44.39kW as compared to 28.6kW by both the hybrid and PSO approach and for 3 DG placement the reduction in line loss by the hybrid and PSO approach are 11.7kW and 11.8kW respectively as compared to 22.29kW by the improved analytical (IA) method. In general the proposed hybrid approach provides better results in comparison with PSO technique and improved analytical method.

These results are obtained with the help of the proposed hybrid approach and verified by PSO technique and improved analytical results. The 33-bus system has a lagging power factor load. Hence the power factor of DG will be leading.

TABLE I MULTIPLE TYPE-III DG PLACEMENT BY HYBRID APPROACH AND PSO TECHNIQUE

Case	Approach	Bus Location	DG size (MVA)	Optimal p.f.	Power loss (kW)	% Loss Reduction
No DG					211	0
1 DG	Hybrid	6	3.028	0.82	67.9	67.82
	PSO	6	3.035	0.82	67.9	67.82
	IA [19]	6	3.107	0.82	67.9	67.82
2 DG	Hybrid	13	1.039	0.91	28.6	86.44
		30	1.508	0.72		
	PSO	13	0.914	0.91	28.6	86.44
		30	1.535	0.73		
	IA [19]	6	2.195	0.82	44.39	78.98
		30	1.098	0.82		
3 DG	Hybrid	13	0.873	0.90	11.7	94.45
		24	1.186	0.89		
		30	1.439	0.71		
	PSO	13	0.863	0.91	11.8	94.41
		24	1.188	0.90		
		30	1.431	0.71		
	IA [19]	6	1.098	0.82	22.29	89.45
		30	1.098	0.82		
		14	0.768	0.82		

2. Voltage Profile

Figures 1-3 also show the variations in minimum and maximum voltages before and after the placement of 1 DG, 2 DGs and 3 DGs of Type-III for 33-bus test system respectively.

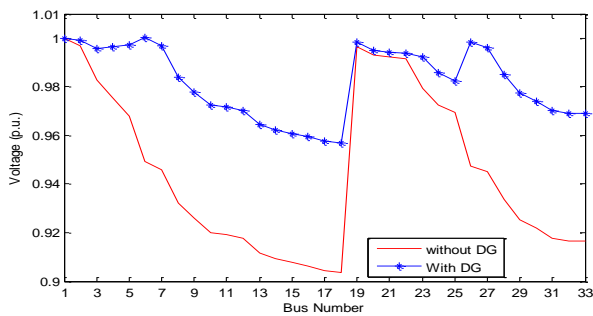


Fig. 1 Voltage profile before and after 1DG placement

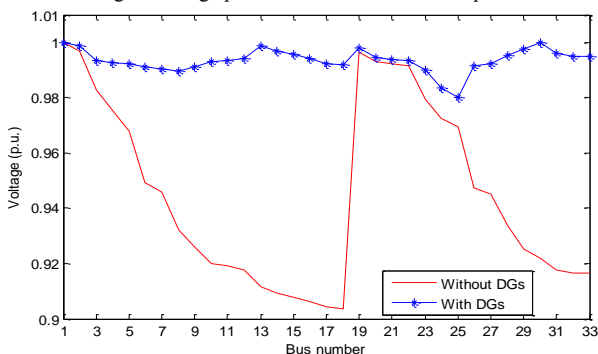


Fig. 2 Voltage profile before and after 2DGs placement

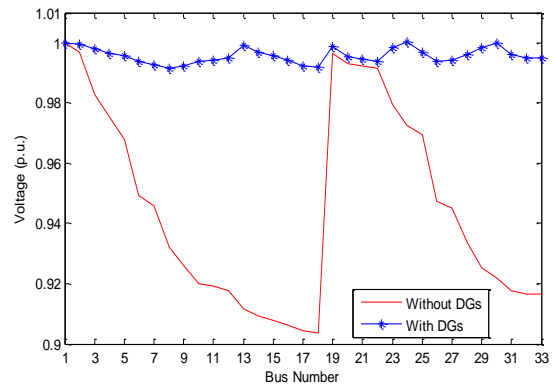


Fig. 3 Voltage profile before and after 3DGs placement

It is observed that in all the cases the voltage profile improves, when the number of DG units installed in the system are increased, while satisfy all the current and voltage constraints.

V. CONCLUSION

This paper has presented the allocation of multiple DGs using hybrid and PSO approach for active and reactive power compensation to minimize the line losses in the primary distribution networks. The results obtained by hybrid and PSO approach have also been verified using the fast analytical approach. The number of DG units with appropriate sizes at optimal locations can reduce the losses to a considerable amount. The optimal power factor which results minimum power loss has also been evaluated. The

proposed approach of optimal placement of multiple DGs not only reduces the line losses but also minimize the sizes of DGs with satisfaction of the permissible voltage limits. In the age of integrated grid, the placement and analysis of multiple DGs give guidance for optimal economic planning and operation of power system.

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