THE OPTIMAL PLANNING OF DISTRIBUTED GENERATION USING OPF AND BUTTERFLY-PSO (BF-PSO) TECHNIQUE

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Abstract: *In the recent scenario many researchers are working in the field of distributed generation (DG) technology but economy, performances, security and reliability of the system are the more challenging issues. This paper presents the optimal planning i.e. optimal location and sizing of distributed generation (DG) based on the combined optimal power flow (OPF) and Butterfly-particle swarm optimization (Butterfly-PSO or BF-PSO) techniques. The multi-objective function has been formulated on the basis of the various system indices. These indices decide the performance and quality of the system. The proposed method has been implemented on the 33-bus radial system. The validity of the method has been confirmed by comparing the results with already published methods. The results show that the system overall generating cost and the nodal price are more economical. Also the reduction in losses (active and reactive power loss) and the improvement in overall performance are more effective than the other's work which is given in the results.*

Keywords: *Distributed Generation (DG), Optimal Location and Sizing, Optimal Power Flow (OPF), Butterfly-particle swarm optimization (Butterfly-PSO or BF-PSO).*

1. Introduction

The different types of distributed generation (DG) technologies such as small, medium and large distributed generation are possible in the radial and mesh system. The combinations of distributed generation technology with the renewable and non-renewable energy sources are possible. The multi-objective function based on system performance indices to determine the location and size of distributed generation with the load models in the distribution system is given by Deependra Singh et al [1]. The genetic algorithm (GA) based optimization technique has been implemented on the 16 and 37-bus distribution systems. The performance base multi-objective function approach for optimal sizing and location of multi-distributed generation (multi-DG) units in distribution systems with load models is explained by A.M. El-Zonkoly [2]. The particle swarm optimization (PSO) based optimization technique has been implemented on the 38-bus radial system and IEEE 30-bus meshed system. The performance indices including short circuit level, active power loss, reactive power losses, the voltage profile, the line loading and the Mega Volt Ampere (MVA) capacity. R. Srinivasa Rao et al [3], introduced a new concept for the network reconfiguration problem considering the distributed generation (DG). The problem objectives in this work are to minimize the real power loss and voltage profile improvement of the distribution system. The Harmony Search Algorithm (HSA) has been used for optimal locations of DG and optimal reconfiguration on the 33 and 69-bus distribution systems.

The concept of the Butterfly-particle swarm optimization (Butterfly-PSO or BF-PSO) technique based on the characteristic behavior, intelligence and the butterfly swarm search process for food hence attracting towards food (or nectar) source is given by A.K. Bohre et al [4-5]. They have included several modern parameters such as sensitivity, probability, etc. The motivation towards the butterfly based swarm optimization is searching of food processing, intelligence and behavior. The searching process of butterflies basically concentrated on the food source that is nectar sources. The butterflies have the natural sensitivity to sense the nectar probability. The butterfly develops an interactive intelligent system with high communication to find the optimal solutions.

S. Hasanpour et al [6] has given the new methodology to allocate the reactive power cost. The active and reactive power cost calculation of the generators based on tracing algorithm, which was validated on the IEEE 9-bus system. Rajendra Prasad Payasi et al [7] studied comparison of different types of distributed generation (DG) units in the distribution system with different load models and seasonal mixed load models. The analysis carried out by the incremental power flow and exhaustive search method on 38-bus test system. C. A. Cañizares et al [8] analyzed the parameters of a competitive electricity market and reactive power dispatch problems. The objective of presenting these parameters is to minimize the total system cost. The study of 32-bus CIGRE benchmark system has been grid considered. The mitigation of active and reactive power loss in distribution system using Particle Swarm Optimization (PSO) technique has been proposed by Satish Kansal et al [9]. The optimal DG and Capacitor placement have done to achieve this goal, which is tested on the 33-bus distribution system. The calculation of available transfer capability (ATC) for a transmission system with the new set of distribution factors has been developed by Ashwani Kumar et al [10]. The distribution factors such as the power transfer distribution factors (PTDF) and the voltage distribution factors have been studied on the IEEE 24-bus Reliability Test System (RTS) system and a 75-bus Indian system network. The available transfer capability (ATC) in a competitive electricity market using optimal power flow based approach has been proposed Ashwani Kumar et al [11] in which impacts unified power flow controller (UPFC) and Sen Transformer (ST) are used to obtain the ATC, power transfer distribution factors (PTDF) and other security parameters with the ZIP load model. This work has been carried out on the IEEE 24-bus RT-System.

J. Z. Zhu [12] proposed the active power loss minimization with the distribution network reconfiguration (DNRC) based on the genetic algorithm (GA). The radial distribution network load flow (RDNLF) has been used as a load flow method in the 16-bus and 33-bus distribution system. The optimal location and sizing of DG and optimal reconfiguration problem in radial distribution systems with and without DG to minimize the power loss using ant colony search algorithm (ACSA) is reported by Vahid Rashtchi et al [13]. This work is implemented on the 17-bus and 33-bus distribution system. The power flow and optimal power flow is solved with the Matpower tool described by Ray D. Zimmerman et al [14]. The MATLAB-Matpower tool intended as a programming, simulation tool for researchers and educators that is easy to use and modify. The impact of various index based multi-objective on the optimal location and size of DG in distribution systems is described by Ochoa et al [15]. M. Vatankhah et al [16] presented optimum size and location of DGs are determined for loss reduction in distribution systems using GA. A. Aissaoui et al [17] reported optimal location and size of DG for reducing active power losses using a heuristic two-step method which is tested on 33-bus system for 100% DG penetration.

This paper presents the optimal installation of distributed generation (DG) as an active power and reactive power sources, considering combined renewable power sources such as solar and wind etc. The optimal allocation and sizing of distributed generation (DG) in the 33-bus radial distribution system with the different objective indices such as Generation Cost Index (CTI), Active Power Loss Index (PLI), Reactive Power Loss Index (QLI), Voltage Deviation Index (VDI), Load Balancing Index (LBI) and Shift Factor Index (SFI) based multi-objective function. The nodal prices of the system is also investigated with-DG and without-DG conditions. The achieved results on the radial distribution system show that the performance and economy of the whole system are improved considering with the DG.

2. The Optimal Power Flow (OPF) and Nodal Pricing

2.1 AC Optimal Power Flow (AC-OPF)

The optimal power flow (OPF) based on the NR-method to minimize the total generation cost C_f. The total generation cost is defined as a second order polynomial generation cost function. The cost function based on the active and reactive power generation cost is:

$$C(P_G) = a + b \times P_G + c \times P_G^{\,2} \quad (1)$$

$$C(Q_G) = a' + b' \times Q_G + c' \times Q_G^{\,2} \quad (2)$$

$$C_f = \min \sum_{k=1}^{G} \left(C(P_{Gk}) + C(Q_{Gk}) \right) \quad (3)$$

The power balance equations with-out distributed generation at j[th] bus (DG) is:

$$\sum P_{Dj} + \sum P_{Lj} - \sum_{i=1}^{n} |V_j||V_i||Y_{ji}| \cos(\theta_{ij} + \delta_i - \delta_j) = 0 \quad (4)$$

$$\sum Q_{Dj} + \sum Q_{Lj} + \sum_{i=1}^{n} |V_j||V_i||Y_{ji}| \sin(\theta_{ij} + \delta_i - \delta_j) = 0 \quad (5)$$

Hence, the constraints with-DG can be given as:

$$\sum P_{Dj} + \sum P_{Lj} - P_{DGj} - \sum_{i=1}^{n} |V_j||V_i||Y_{ji}| \cos(\theta_{ji} + \delta_i - \delta_j) = 0 \quad (6)$$

$$\sum Q_{Dj} + \sum Q_{Lj} - Q_{DGj} + \sum_{i=1}^{n} |V_j||V_i||Y_{ji}| \sin(\theta_{ji} + \delta_i - \delta_j) = 0 \quad (7)$$

$$\delta_{\min} \le \delta_j \le \delta_{\max}$$

$$V_{\min} \le V_j \le V_{\max}$$

$$P_{\min} \le P_j \le P_{\max}$$

$$Q_{min} \le Q_j \le Q_{\max}$$

$$P_{DG\min} \le P_{DGj} \le P_{DG\max}$$

$$Q_{DG\min} \le Q_{DGj} \le Q_{DG\max}$$

Where, P_j and Q_j are the j-th bus real and reactive power flow. P_{Dj} and Q_{Dj} the j-th bus real and reactive demand. V_i and V_j are the voltage magnitude value at the *i-th* and *j-th* bus. P_{DGj} is the real power of DG placed at j-th bus. δ_i, δ_j are The angles of *i-th* and *j-th* bus voltage. Y_{ji} is the *ji-th* element magnitude in bus admittance matrix. θ_{ji} is the angle of the *ji-th* element in bus admittance matrix. And n is the total number of buses.

2.2 Combined Real and Reactive Power for Uniform nodal pricing

By considering the j-th dispatchable load is modeled as a constant power factor, hence the ratio of reactive to real demand is a constant. Then the real and reactive power consumption of this load can be thought of as a single\combined or bundled commodity. The uniform nodal price value can be expressed on the basis of per MW or per MVAr [14]. Let us assume that the load is located at bus j and the prices of real and reactive power are λ_{Pj} and λ_{Qj} respectively. So, the combined or bundled power χ can be given as:

$$\chi = \lambda_{Pj} P_{Dj} + \lambda_{Qj} Q_{Dj} \quad (8)$$

$$\chi = \lambda_{Pj} P_{Dj} + \lambda_{Qj} \frac{Q_{Dj}}{P_{Dj}} P_{Dj} \quad (9)$$

$$\chi = \left(\lambda_{Pj} + \lambda_{Qj} k_j\right) P_{Dj} \quad (10)$$

Where, $k_j = \frac{Q_{Dj}}{P_{Dj}} = \text{constant}$. Also, in other words the per MW price of the bundled commodity is $\lambda_{Pj} + k_j * \lambda_{Qj}$. Similarly, the per MVAr price is $\lambda_{Pj}/k_j + \lambda_{Qj}$.

3. The Multi-Objective Problem Formulation and Performance Indices

To determine the optimal location and sizing of the distributed generation (DG) in the radial and meshed system with the various objectives achieves by the following multi-objective function (F_{mo}).

$$F_{MO} = k_1 \times CTI + k_2 \times PLI + k_3 \times QLI + k_4 \times VDI + k_5 \times LBI + k_6 \times SFI \quad (11)$$

Also, $k_1 + k_2 + k_3 + k_4 + k_5 + k_6 = 1$, The k_1, k_2, k_3, k_4, k_5, k_6 are the indices weight factors. The detail concepts for selecting the weight factor of the indices given in references [1, 2, and 15]. All these weight factors are decided on the basis of the individual impacts and the importance of the index while installing the DG. The main aim is to minimize the overall power losses of the system, so the active power loss index gets highest weight is 0.28, after that second highest weight get is 0.20. The voltage deviation index (VDI) gets weight of 0.16, due to maintain the power quality and voltage profile of the system. The load balancing index (LBI) indicates the power balance at particular bus and loads, hence it gets a weight of 0.14. The total generation cost (CTI) also an important factor for the economy purpose due to that it gets a weight of 0.12. The shift factor index (SFI) decides the change in power at other buses due particular injection of the DG size at the bus; hence it gets a weight of 0.10.

3.1 Total Generation Cost Index (CTI)

The total cost index (CTI) gives the overall economic performance of the system when DG is installed. It's defined by assuming CT_{DG} and CT_{No-DG} are the total generation cost value with DG and with-out DG of the system.

$$CTI = \frac{CT_{DG}}{CT_{No-DG}} \quad (12)$$

3.2 Active Power Loss Index (PLI)

The active power loss index (PLI) decides the performance of the active power loss of the whole system in the different cases. It can be expressed by considering PL_{DG}, and PL_{No-DG} are the active power losses with DG and with-out DG of the system.

$$PLI = \frac{PL_{DG}}{PL_{No-DG}} \quad (13)$$

3.3 Reactive Power Loss Index (QLI)

The the total reactive power loss performance of the system described by the reactive power loss index (QLI). It's given by considering QL_{DG}, and QL_{No-DG}

as the reactive power losses with DG and with-out DG of the system.

$$QLI = \frac{QL_{DG}}{QL_{No-DG}} \qquad (14)$$

3.4 Voltage Deviation Index (VDI)

This voltage profile performance throughout the system given by the voltage deviation index (VDI). It can be given on the basis of the deviation of system voltage from the reference or rated value (V_{reff}). The minimum the voltage deviation index denotes the better the system performance and improvement in voltage profile. This index can be given as:

$$VDI = \max_{j=2}^{n} \left(\frac{V_{reff} - V_{DGj}}{V_{reff}} \right) \qquad (15)$$

Where, n-is the total no. of buses. The V_{reff} and V_{DGj} are the reference voltage and the system voltage value in pu with DG respectively.

3.5 Load Balancing Index (LBI)

In the recent scenario the load demand is increasing day by day in the system. So, the management and balance of load demand are the major issue for the reliable operation of the system with the system capability limits. The load balancing index (LBI) has been given to the concept based on available power at any bus, which is distributed between the loads and next bus. The available power at any bus can be given as:

$$S_j = \sqrt{P_j^{\,2} + Q_j^{\,2}} \qquad (16)$$

Then load balancing index is as:

$$LBI = \max_{j=1}^{n-1} \left(\frac{S_{DGj}}{S_{No-DGj}} \right) \qquad (17)$$

Where, S_{DGj} and S_{No-DGj} are the available power with DG and with-out DG respectively and n is the number of buses.

3.6 Shift Factor Index (SFI)

The AC power flow shift factor also called as a power transfer distribution factor (PTDF) is the sensitivity of the power flows. In other words, it indicates the effects of the power flows in all other lines due to the particular power transactions. The relation between PTDF and available transfer capacity (ATC) is inverse relation, hence minimum PTDF shows the maximum ATC. Let us presume that the change in power due to particular transaction Δt is Δx, then the AC power flow shift factor is:

$$SF \; or \; PTDF = \frac{\Delta x}{\Delta t} \qquad (18)$$

The installation of DG with particular size will inject some power say x_{inj} at bus and due to this injection the change in power is Δx, then shift factor index (SFI) can be given as:

$$SFI = \max_{\substack{j=1 \\ j \neq slack\, and \\ pv\, bus}}^{n-1} \left| \frac{\Delta x_j}{x_{inj,j}} \right| \qquad (19)$$

4. The Butterfly Particle Swarm Based Optimization (BF-PSO) Techniques

The Butterfly-PSO (BF-PSO) algorithm is fundamentally founded on the nectar probability and the sensibility of the butterfly swarm. The BF-PSO consists of intelligent behavior of the butterfly to find out the optimal quantity of ambrosia. The butterfly particle swarm optimization learning algorithm (BF-PSO) is applied to acquire the concept of optimal solutions not simply applying the random parameters and acceleration parameter, as well as it utilizes the result of additional parameter's probability and sensitivity for fast convergence and more accurate optimal solution. In operation for calculating the optimal solution, the degree of node in every flight of butterfly assumed as approximately equal to 1 because assuming the maximum connectivity in each trajectory. The butterfly swarm based search process investigates the optimal location depending upon the sensitivity of butterfly toward the flower and the probability of nectar. The information about the optimal solution communicates directly or indirectly between the all butterflies by different means of communication intelligence (such as dancing, colors, chemicals, sounds, physical action and natural processes).

The butterfly leaning based particle swarm optimization algorithm has developed to ascertain the optimal solutions including the random parameters, acceleration coefficients, probability, sensitivity, lbest and gbest. In the Butterfly-PSO, lbest solutions are selected by the individual’s best solution. Afterward that the gbest solution identified based on the respective fitness. The locations (position) of the nectar (food) source represent the probable optimal solution for the problem and the amount of nectar (food) represents the corresponding fitness. The detail implementation of the Butterfly-PSO (BF-PSO) technique is given below. The general ranges of the sensitivity and probability are considering from 0.0 to 1.0. The velocity limits can be set based on the variable boundary in the solution.

Hence the use of inertia weight, sensitivity and probability as a use of iterations can be given as:

$$w_k = 0.9 - ((0.9 - 0.4) / ITER_{max}) * ITER_k \quad (20)$$

$$s_k = exp - (ITER_{max} - ITER_k) / ITER_{max} \quad (21)$$

$$p_k = FIT_{gbest,k} / \sum(FIT_{lbest,k}) \quad (22)$$

Where, $ITER_{max}$ = maximum number of iterations, and $ITER_k$ = k^{th} iteration count. And, $FIT_{lbest,k}$ =Fitness of local best solutions with k^{th} iteration, $FIT_{gbest,k}$ = Fitness of global best solutions with k^{th} iteration.

The Butterfly-PSO (BF-PSO) equations to update the velocity and the position are depends on the sensitivity of the butterfly and the probability of nectar, which can be explained as:

$$v'_k = w_k.v_{k-1} + s_k(1 - p_k)c_1 r_1(x_{lbest,k-1} - x_{k-1}) + p_k c_2 r_2(x_{gbest,k-1} - x_{k-1}) \quad (23)$$

$$x_k = p_k.x_{k-1} + \alpha_k.v'_k \quad (24)$$

Where α_k is a varying probability coefficient, α_k=*rand*$*p_k$, rand-is the random number [0, 1].

The flow chart to find the optimal sizing and location of DG using Butterfly-PSO (BF-PSO) technique is given in figure-1; and the detail algorithm can be given as:

1. Read and input the system data (bus data, line data, generation data etc.).
2. Run and execute the optimal power flow (OPF) results in case of with-out DG.
3. Initialize the BF-PSO parameters c_1, c_2, w, p_k, and s_k. And the butterfly particle positions can be defined as:

   $$x = [P_{dg1}, P_{dg2}, ...P_{DGs}; Q_{dg1}, Q_{dg2}, ...Q_{DGs}] \quad (25)$$

   Where, s is the number of butterfly swarm.
4. Now, consider the for loop for the buses up to the maximum no. of buses of the system excluding the slack and pv buses.
5. Set-up the main while loop of the Butterfly-PSO technique and sets iteration count iteration=0, and also start with iteration= iteration+1.
6. Update the sensitivity and probability values of solution algorithm.
7. Update the butterfly particle velocity and the positions with-DG condition and check for constraints limit.
8. After that call the optimal power flow (OPF) and execute the opf results with-DG condition.
9. Calculate the all indices value for the multi-objective function with each butterfly swarm at each bus.
10. Evaluate the fitness value for each particle position considering the multi-objective function as a fitness function at each bus.
11. Compare the local best (lbest) of each particle and global best (gbest) in the whole butterfly swarm.
12. Find the global optimal value of the fitness function and the corresponding global optimal parameters or particle positions at every bus.
13. And check for termination criteria, if otherwise, repeat algorithm from step 3 to step 12.
14. Repeat this procedure up to maximum number of buses.
15. Record and save the all output data of the system.

5. Results and Discussions

The proposed algorithm is implemented on the 33-bus radial system given in [3, 9, 12 and 13]. The base MVA during this work is 100 MVA. The range of DG size is considered from 0 to 50 for both MW and Mvar, with DG operate at an unspecified power factor. The allocation of a DG is considered on the load buses not on the slack bus and voltage-controlled buses in the system. The all results for proposed methodology are carried out with MATLAB (2009a)/Matpowe4.1 tool with the system configuration windows-8.1, AMD-E1-1500APU, 1.48 GHz, 2.0 GB RAM.

5.1 The Radial 33-Bus Distribution System

The detail information about the 33-bus radial system has given in [3, 9, 12 and 13]. The study considers the tie switches 33, 34, 35, 36, and 37 are open. The proposed Butterfly-PSO/BF-PSO algorithm applied to minimize the multi-objective function given in equation (11). The optimal minimum value of the multi-objective function decides the optimal value of indices and based on these optimal index values the optimal location and size of DG is determined.

The proposed Butterfly-PSO technique has been implemented with swarm size is 30, total number of iterations are 50 and the active and reactive power are two variables of single-DG hence problem dimention is 2. The termination criteria for proposed algorithem are maximum number of iterations for inner loop and the maximum numbre of buses for outer loop as indicated in algorithm flow chart which is given in figure-1.

The performance results of 33-bus radial system shown in figures from 2 to 9. The variation of multi-objective function value with their respective index at a particular bus shown in figure-2 and also the DG size, active power loss and active power loss on the respective bus are given in figure-3. The result shows that the minimum value of the multi-objective function is obtained at bus 6. Similarly the variation of total generation cost and the nodal price of active and reactive power with and without DG is respectively given in figure-4, figure-5 and figure-6. The results in figure-4 indicates that the minimum value of total generation cost obtained at bus 6. The nodal prices of active and reactive power with-DG are lower as compared to without-DG case for 33-bus radial system which is shown in figure-5 and figure6.

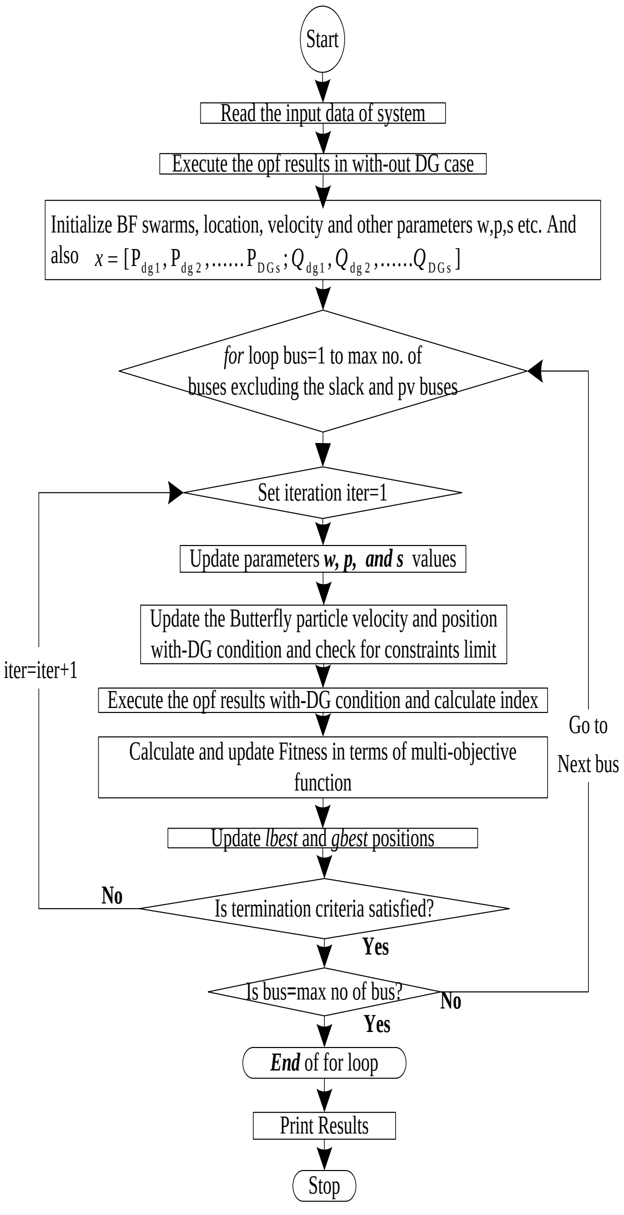

Figure-1: The butterfly-PSO (BF-PSO) algorithm flow chart

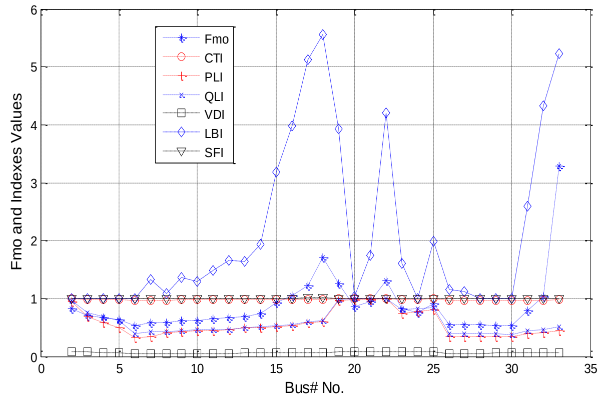

Figure-2: The variation of multi-objective function and various indices at different buses for 33-bus radial system

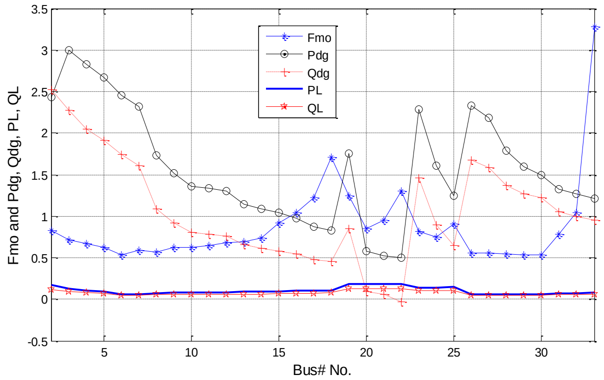

Figure-3: The variation of DG size, and system losses with multi-objective function value of 33-bus radial system

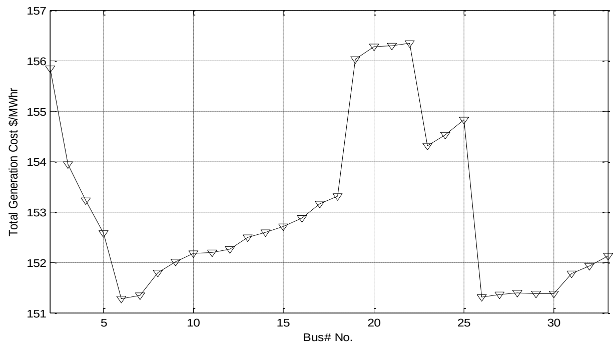

Figure-4: The total generation cost curve at buses with-DG for 33-bus radial system

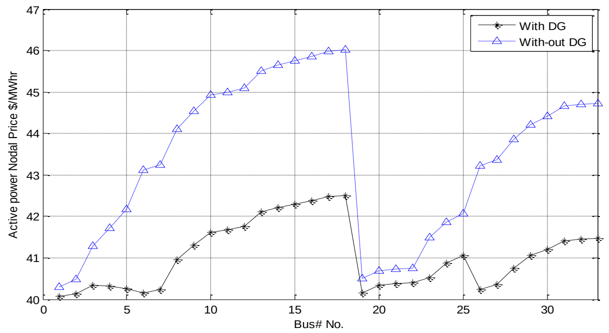

Figure-5: The nodal price of active power with and without DG for 33-bus radial system

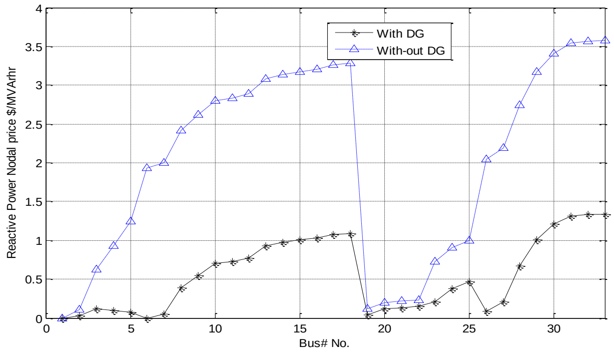

Figure-6: The nodal price of reactive power with and without DG for 33-bus radial system

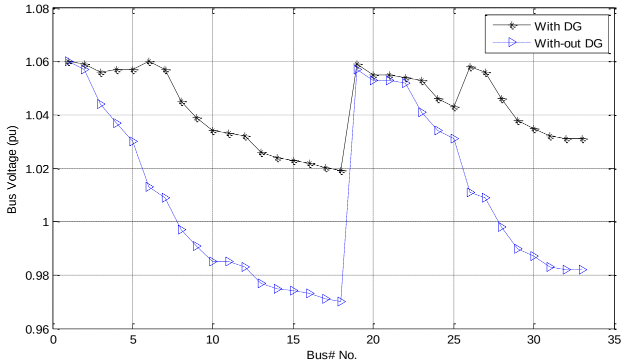

Figure-7: The voltage profile with and without DG for 33-bus radial system

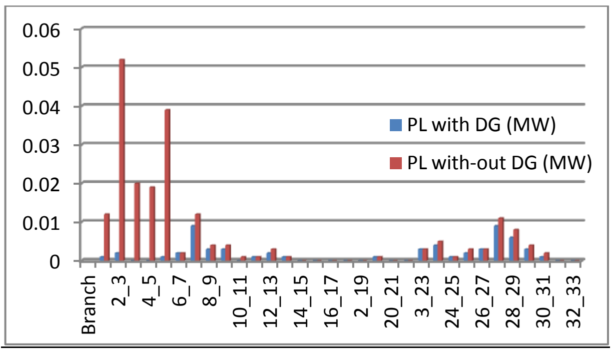

Figure-8: The active power loss with and without DG for 33-bus radial system

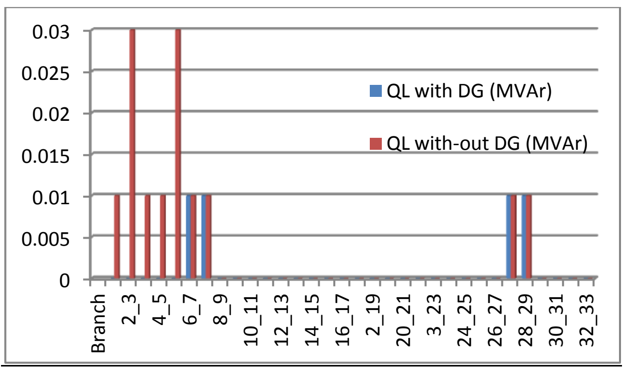

Figure-9: The reactive power loss with and without DG for 33-bus radial system

The voltage profile values with-DG are more as compare to without-DG condition of 33-bus radial system which is shown in figure-7. Similarly, the active and reactive power loss with-DG obtains the lower value as compared to without-DG condition of 33-bus radial system which is shown in figure-8 and figure-9. The optimum value of all the parameters using proposed Butterfly-PSO/BF-PSO algorithm is given in table-1, table-2, and table-3 for 33-bus radial system. The minimum value of the objective function obtains at bus 6 with their optimal index value which is given in the table-1 by green shaded row. The whole table-1 shows the global optimal solution values of the multi-objective function and their indices at each bus. The table-2 shows the DG size (PDG, QDG), total generation cost (CT) and loss values (PL, QL) at each bus with corresponding objective function and index value. The table-3 shows the voltage, active and reactive power nodal price on buses with and without DG case at each bus with corresponding objective function and index value of 33-bus radial system.

The table-1 gives possible optimal solution results of the Butterfly-PSO/BF-PSO technique on each and every bus excluding the slack bus. These results conclude that the optimal value of the multi-objective function is 0.531234 at bus-6, which is the more optimal value from all of the buses. The corresponding the optimal value of the multi-objective function, the value of CTI, PLI, QLI VDI, LBI and SFI respectively, are 0.966572, 0.326145, 0.387892, 0.038297, 0.999987 and 1.002187 at bus-6. Similarly, the table-2 shows the possible optimal solution results of the Butterfly-PSO/BF-PSO technique. The corresponding the optimal value of the multi-objective function the active power DG size (PDG), the reactive power DG size (QDG), total generation cost with-out DG (CT-No-DG in $/MW/hr), total generation cost with DG (CT-DG in $/MW/hr), the active power loss with DG (PL-DG) and the reactive power loss with DG (QL-DG) values at bus-6 respectively are 2.4532, 1.7452, 156.509379, 151.2776, 0.060151 and 0.048482. The table-3 gives the optimal values of the voltage with and without DG are 1.06 pu and 1.013 pu at bus-6. The active power nodal price with and without DG are 40.151 and 43.113 $/MW/hr. The reactive power nodal price with and without DG are 0 and 1.932 $/MVAr/hr. Also, the table-4 shows comparative results analysis between the proposed methodology and the existing one.

6. Conclusions

The proposed Butterfly-PSO/BF-PSO optimization technique has been developed for the 33-bus radial system. This methodology has implemented in multi-objective function based on system performance indices to determine the optimal allocation and sizing of the distributed generation (DG). The comparative analysis of the results for the proposed and existing methodology is given in table-4 for the 33-bus radial system. This comparative analysis of the 33-bus radial system shows the active power loss reduction is 67.79 % with the existing method and the active power loss reduction is 71.49 % with the proposed method which is better than the existing method. And the reactive power loss reduction with the existing method is 61.69 %, and the reactive power loss reduction with the proposed method is 66.12 % which are superior results than the existing method. The results analysis clarifies that the proposed methodology is the more effective to improve the system performance, such as power loss reduction, voltage profile improvement, improve load balancing capacity, good economy, the optimal shift factor value hence increases ATC and reduction in MVA flows and MVA intake from the system or grid.

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Table-1: The value of multi-objective function (Fmo) and indices at buses for 33-bus radial system

Sr. No.	Obj. Fun. (Fmo)	Bus	CTI	PLI	QLI	VDI	LBI	SFI
1	0.828258	2	0.995723	0.943294	0.95626	0.082672	0.999999	1.001698
2	0.709413	3	0.98356	0.677595	0.750264	0.070124	0.999998	1.003874
3	0.666852	4	0.979025	0.584613	0.67688	0.062392	0.999998	1.003183
4	0.627795	5	0.974873	0.499172	0.609549	0.055349	0.999998	1.002769
5	0.531234	6	0.966572	0.326145	0.387892	0.038297	0.999987	1.002187
6	0.586995	7	0.967007	0.336722	0.422197	0.035233	1.330628	1.003076
7	0.57232	8	0.969885	0.399172	0.431803	0.043808	1.075292	1.002545
8	0.622694	9	0.971262	0.427196	0.445427	0.047165	1.35441	1.002791
9	0.622442	10	0.972254	0.446766	0.45574	0.049331	1.295075	1.003256
10	0.650894	11	0.972432	0.450247	0.456338	0.049494	1.490116	1.003303
11	0.675719	12	0.972824	0.457914	0.458986	0.05002	1.64778	1.002746
12	0.69002	13	0.974351	0.48822	0.487751	0.052793	1.643627	1.002917
13	0.737703	14	0.974921	0.499419	0.504564	0.05383	1.935542	1.003735
14	0.92033	15	0.975745	0.516	0.521916	0.054805	3.180074	1.003982
15	1.041304	16	0.976783	0.536922	0.540143	0.055868	3.974201	1.00397
16	1.223409	17	0.978579	0.57288	0.594834	0.057847	5.119796	1.005789
17	1.714027	18	0.979536	0.592186	0.61115	0.058659	8.560525	1.005821
18	1.250418	19	0.996924	0.970531	0.984679	0.083927	3.919186	0.999878
19	0.851865	20	0.998489	0.98665	0.98969	0.084643	1.032088	0.998108
20	0.951977	21	0.998601	0.987675	0.990643	0.084554	1.743525	0.998446
21	1.300903	22	0.998913	0.993109	0.999098	0.08454	4.213842	0.996793
22	0.821055	23	0.985902	0.736672	0.802345	0.073946	1.599887	1.001943
23	0.749759	24	0.987348	0.767495	0.819042	0.077327	0.999999	1.001984
24	0.904255	25	0.989227	0.803661	0.845484	0.079098	1.98988	1.001869
25	0.554119	26	0.966776	0.33161	0.390857	0.040337	1.145886	1.00206
26	0.553682	27	0.96704	0.338216	0.395157	0.042881	1.120374	1.001919
27	0.540418	28	0.967345	0.34555	0.396726	0.050221	1	1.002016
28	0.536839	29	0.967158	0.340914	0.382983	0.053392	1	1.001845
29	0.536746	30	0.967237	0.341939	0.38004	0.054687	0.999999	1.001772
30	0.786891	31	0.96977	0.393974	0.442394	0.059266	2.585774	1.002358
31	1.040336	32	0.970663	0.412316	0.467639	0.060804	4.32066	1.002597
32	3.284873	33	0.971942	0.43877	0.516593	0.063262	5.226097	1.002902

Table-2: The DG size, generation cost and loss values at buses for 33-bus radial system

Bus	PDG MW	QDG MVAr	CT-No-DG $/MW/hr	CT-DG $/MW/hr	PL-DG MW	QL-DG MVAr
2	2.4308	2.5185	156.509379	155.8401	0.173971	0.119521
3	2.9955	2.273	156.509379	153.9364	0.124969	0.093774
4	2.8222	2.0505	156.509379	153.2266	0.10782	0.084602
5	2.6701	1.9115	156.509379	152.5768	0.092062	0.076187
6	2.4532	1.7452	156.509379	151.2776	0.060151	0.048482
7	2.314	1.6111	156.509379	151.3457	0.062102	0.05277
8	1.7342	1.0889	156.509379	151.7961	0.073619	0.05397
9	1.5196	0.9207	156.509379	152.0116	0.078788	0.055673
10	1.3604	0.8032	156.509379	152.1669	0.082397	0.056962
11	1.3349	0.786	156.509379	152.1947	0.083039	0.057037
12	1.2975	0.7616	156.509379	152.2561	0.084453	0.057368
13	1.1457	0.6573	156.509379	152.4951	0.090042	0.060963
14	1.0906	0.618	156.509379	152.5842	0.092108	0.063065
15	1.0382	0.5826	156.509379	152.7133	0.095166	0.065233
16	0.9801	0.5463	156.509379	152.8757	0.099024	0.067512
17	0.8749	0.4781	156.509379	153.1568	0.105656	0.074347
18	0.8301	0.4525	156.509379	153.3066	0.109217	0.076387
19	1.7489	0.8552	156.509379	156.0279	0.178995	0.123073
20	0.5759	0.0943	156.509379	156.2729	0.181967	0.1237
21	0.5232	0.0565	156.509379	156.2905	0.182157	0.123819
22	0.5	-0.029	156.509379	156.3392	0.183159	0.124876
23	2.281	1.4572	156.509379	154.3029	0.135864	0.100284
24	1.6118	0.89	156.509379	154.5292	0.141549	0.102371
25	1.2415	0.6442	156.509379	154.8233	0.148219	0.105676
26	2.3305	1.6722	156.509379	151.3096	0.061159	0.048853
27	2.1817	1.587	156.509379	151.3508	0.062377	0.04939
28	1.7864	1.3674	156.509379	151.3986	0.06373	0.049586
29	1.5986	1.2688	156.509379	151.3693	0.062875	0.047868
30	1.4985	1.2183	156.509379	151.3817	0.063064	0.047501
31	1.3216	1.0489	156.509379	151.7781	0.072661	0.055294
32	1.2693	1.0022	156.509379	151.9178	0.076043	0.058449
33	1.2079	0.9519	156.509379	152.118	0.080922	0.064568

Table-3: The voltage, active and reactive power nodal price on buses with and without DG for 33-bus radial system

Bus No.	Voltage with-DG pu	Voltage No-DG pu	Nodal price of P with-DG $/MW/hr	Nodal price of P No-DG $/MW/hr	Nodal price of Q with-DG $/MVAr/hr	Nodal price of Q No-DG $/MVAr/hr
1	1.06	1.06	40.074	40.304	0	0
2	1.059	1.057	40.13	40.474	0.026	0.105
3	1.056	1.044	40.331	41.293	0.116	0.625
4	1.057	1.037	40.309	41.729	0.101	0.932
5	1.057	1.03	40.266	42.166	0.071	1.242
6	1.06	1.013	40.151	43.113	0	1.932
7	1.057	1.009	40.244	43.24	0.05	2.001
8	1.045	0.997	40.959	44.115	0.392	2.419
9	1.039	0.991	41.3	44.533	0.551	2.615
10	1.034	0.985	41.618	44.922	0.702	2.801
11	1.033	0.985	41.672	44.988	0.729	2.833
12	1.032	0.983	41.767	45.103	0.774	2.887
13	1.026	0.977	42.102	45.517	0.928	3.078
14	1.024	0.975	42.212	45.655	0.976	3.138
15	1.023	0.974	42.294	45.757	1.004	3.173
16	1.022	0.973	42.375	45.857	1.035	3.211
17	1.02	0.971	42.477	45.986	1.076	3.263
18	1.019	0.97	42.511	46.028	1.091	3.282
19	1.059	1.057	40.157	40.501	0.038	0.117
20	1.055	1.053	40.34	40.687	0.12	0.2
21	1.055	1.053	40.374	40.721	0.135	0.215
22	1.054	1.052	40.403	40.751	0.148	0.228
23	1.053	1.041	40.525	41.497	0.211	0.725
24	1.046	1.034	40.877	41.871	0.379	0.904
25	1.043	1.031	41.055	42.059	0.464	0.994
26	1.058	1.011	40.238	43.219	0.089	2.04
27	1.056	1.009	40.354	43.359	0.211	2.188
28	1.046	0.998	40.761	43.861	0.665	2.746
29	1.038	0.99	41.052	44.219	1.008	3.169
30	1.035	0.987	41.206	44.406	1.208	3.412
31	1.032	0.983	41.41	44.66	1.311	3.539
32	1.031	0.982	41.452	44.713	1.333	3.567
33	1.031	0.982	41.463	44.726	1.34	3.576

Table-4: The Comparative analysis of 33-bus radial system

Parameter / Cases		Active power loss (kW)	Active power loss reduction (%)	Reactive power loss (kVAr)	Reactive power loss reduction (%)
With-out-DG (Base case)		211.7	---	143.1	---
With-DG PDG(2.4532 MW) QDG(1.7452MVAr)	Existing	96.76 [3]	52.26 %	---	---
		67.95 [9]	67.79 %	54.79	61.69 %
		139.53 [12]	33.87 %	---	---
		100.4 [13]	52.42 %	---	---
	Proposed (DG at bus 6)	60.151	71.49 %	48.482	66.12 %