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Power Quality Improvement of Distribution System by Optimal Placement of Distributed Generation Using Particle Swarm Optimization and Sensitivity Analysis

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ABSTRACT

Growing concerns over environmental impacts, improvement of the overall network conditions and rebate programs offered by governments have led to an increase in the number of distributed generation (DG) units in commercial and domestic electric power production. It is known that non-optimal size and non-optimal placement of DG units may lead to high power loss, bad voltage profiles and harmonic propagations. So, this paper aims at determining optimal DG allocation and sizing. To do so, the heuristic optimization technique named Particle Swarm Optimization (PSO) is used as the solving tool to minimize simultaneously the economic cost of overall system by changing sitting and varying sizes of DGs. With respect to voltage profile, THD and loss reduction by using the sensitivity analysis, PSO is used to calculate the objective function and to verify bus voltage limits. To include the presence of harmonics, PSO was integrated with a harmonic power flow algorithm (HPF). The proposed (PSO-HPF) based approach is tested on an IEEE 15-bus radial distribution system and IEEE30 bus system. Finally, the returning of investmental cost is calculated to show the economic justification of DG placement. These scenarios yields efficiency in improvement of voltage profile and reduction of THD and power losses, it also permits an increase in power transfer capacity and maximum loading.

Keywords — Distributed generation, Optimization, Power losses, Harmonic distortion, Sensitivity analysis, Cost reduction

1. INTRODUCTION

In current years, a lot of work has already been done in the electric power system infrastructure and market related to it by using Distribution Generation. Distributed Generation is usually defined as a small-scale power generation facility that is usually connected or installed to the distribution system. While on the other hand to reduce the cost of service, the DGs usually use different modular technologies which are located around a utility's service area. Distributed generation is a technique, which minimizes the amount of power loss in transmission lines by generating the power very close to load centre or may be even transmitted in the same building. Some of the main advantages while installing DG units in distribution level are peak load saving, enhanced system security and reliability, improved voltage stability, grid strengthening, reduction in the on-peak operating cost, reduction in network loss etc [5]. The effects of DG on voltage profile, line losses, short circuit current, amount of injected harmonic and system reliability are to be evaluated separately before installing it in a distribution network. The achievement of such benefits depends greatly on how optimally these distributed generations are installed. Studies have indicated that approximately 13% of generated power is consumed as loss at the distribution level. With the application of loads, the voltage profile tends to drop along distribution feeders below acceptable operating limits. Along with power losses and voltage drops, the increasing growth in electricity demand requires upgrading the infrastructure of distribution systems [4]. So, to reach to these targets, loss reduction and voltage profile improvement, together with THD reduction, planning of the electric system with the presence of DG requires the definition of several factors such as, the best technology to be used, the number and the capacity of the units, the best location, the type of network connection and etc.

The problem of DG allocation and sizing is of great importance. The use of an optimization method capable of indicating the best solution for a given distribution network can be very useful for the system planning engineers. Several optimization techniques have been applied to DG placement and sizing, such as genetic algorithm, neural networks [10], evolutionary programming and heuristic algorithms [8] and analytical based methods [1]. The optimum DG allocation can be modeled as optimum active power compensation. DG allocation studies are relatively new, unlike capacitor allocation [6] that has been studied for many years. The proposed method only optimizes location and considers size of DG as fixed. In this paper, Particle Swarm Optimization algorithm (PSO) is presented as the optimization technique for the allocation and sizing of DG in distribution networks in order to THD and loss reduction in distribution network with minimum economic cost. The 15-bus test feeder and IEEE30 bus systems are selected to test the proposed method. The results show the best position of DG with minimum economic cost.

2. PROBLEM FORMULATION

In this proposed method, Newton Raphson method is used to calculate the power flow between the buses. Newton Raphson method is a commonly used method to calculate the power flow because it takes less number of iterations. The real and reactive power flows between the buses are computed using the equations 1 & 2.

$$Pi = \sum_{K=1}^{N} V_i * V_k (G_{ik} * \text{Cos}\,\theta_{ik} + B_{ik} * \text{Sin}\theta_{ik}) \quad (1)$$

$$Qi = \sum_{K=1}^{N} V_i * V_k (G_{ik} * \text{Sin}\theta_{ik} - B_{ik} * \text{Cos}\,\theta_{ik}) \quad (2)$$

where, N is the total number of buses, V_i & V_k are the voltage at i & k bus respectively, θ_{ik} is the angle between i & k bus, and G_{ik} & B_{ik} are the conductance and susceptance values respectively. The real and reactive power flow between the buses mainly depends on the voltage and angle values.

After calculating the real and reactive powers between the buses, the next step is to calculate the optimal location for fixing DGs in the system. Optimal DG placement and sizing problem is formulated as a constrained nonlinear integer optimization problem. Objective function encompasses the total cost of the total real power loss and that of DG and installation cost.

2.1. Cost Function Formulation

The goal is to minimize the cost of the total real power loss and that of the DG installation and sum of active power of DG injected to system. The cost function is given by

$$F = K_i \,\text{cost}_{install} + \lambda_1 K_p P_{loss} + \sum_{i}^{n} K_{ci} P_{inject\text{-}DGi} \quad (3)$$

Where

K_i-number of DG installed;

$\text{cost}_{install}$-cost of DG installation (Rupees);

K_p-annual cost per unit of the real power loss (Rupees/ KW/year);

P_{loss}-total real power loss (kW);

N-total number of DG to be installed;

K_{ci}-annual cost per unit of the active power injection at bus i (Rupees/kW/year);

$P_{inject\text{-}DGi}$--active power injection at bus i (kW);

λ_1-coefficient factor for balancing the prices of $K_p P_{loss}$ with other terms;

It should be pointed out that the cost of the real power loss per unit is fixed. Also, the cost of the active power injection per unit is constant.

2.2. Optimization Formulation

A multi-objective optimization technique, formulated as a constrained non-linear integer optimization problem, is proposed for DG placement and sizing in a distribution system. The objective is to minimize the total power loss and THDv, as well as to improve the voltage profile of the distribution system. The fitness function is given by Eq. (4):

$$Fmin = \alpha (P_{loss}) + \beta (THDv) \quad (4)$$

where F is the fitness function, P_{loss} is the total power loss, α is the weighted factor for total power loss, THDv is the average total harmonic distortion at all system busbars and β is the weighted factor for THDv

Total real power loss is defined by

$$P_{loss} = \sum_{i=1}^{n} P_{loss\,i} \quad i = 1, 2, 3, ..., n \tag{5}$$

where *n* is the number of lines

The average THDv is defined by

$$THD_v = \frac{\sum_{i=1}^{m} THD_{v\,i}}{m} \tag{6}$$

where *m* is the number of buses.

The total power loss and THDv must be minimized according to the network power flow equations at fundamental and harmonic frequencies. Typical technical constraints, such as the maximum feeder capacity, the short circuit level, the maximum allowable over voltage and voltage drops, and the voltage harmonics, are to be complied with as well. Generally, multi-objective methods provide a set of optimal solutions. For this paper, the sum of the weighted methods is used to decide the relative importance of the objectives in order to obtain the best optimization solution [8]. The weighted factor for total power loss is 0.7 while the average THDv is 0.3. The factor for power loss is greater than that for THDv because the reduction of power loss in distribution networks has a significant impact on economic and technical prospects.

The inequality constraints involve those associated with the bus voltages and the DG to be installed. The bus voltage magnitudes are to be kept within acceptable operating limits throughout the optimization process, as follows:

$$V_{min} \leq |Vi| \leq V_{max} \tag{7}$$

where V_{min} is the lower bound of bus voltage limits, V_{max} is the upper bound of the voltage limits, and $|Vi|$ is the root mean square (RMS) value of the *i*th bus voltage.

The total harmonic level at each bus is to be less than or equal to the maximum allowable harmonic level, as expressed as follows:

$$THD_{vi\,(\%)} \leq THD_{vmax} \tag{8}$$

where THD_v max is the maximum allowable level at each bus.

3. PROPOSED ALGORITHM

With the growing use of DGs in distribution systems, several methods have been used to achieve various objectives in power system optimization problems. In this paper, sensitivity analysis and particle swarm optimization methods are used to determine the optimal placement and sizing of DG in a distribution system. Harmonic load flow analysis was integrated with this optimization technique in order to obtain the fitness functions for the total power loss, average THDv, and the voltage profile.

3.1. Particle Swarm Optimization (PSO)

PSO was formulated by Edward and Kennedy in 1995. The thought process behind the algorithm was inspired by the social behavior of animals, such as bird flocking or fish schooling. PSO is similar to the continuous GA in that it begins with a random population matrix. Unlike the GA, PSO has no evolution operators such as crossover and mutation. The rows in the matrix are called particles (same as GA chromosome). They contain the variable values and are not binary encoded. Each particle moves about the cost surface with velocity [3]. The particles update their velocities and positions based on the local and global best solutions:

$$V_{m,n}^{new} = V_{m,n}^{old} + C_1 r_1 (p_{m,n}^{localbest} - p_{m,n}^{old}) + C_2 r_2 (p_{m,n}^{globalbest} - p_{m,n}^{old}) \quad (9)$$

$$p_{m,n}^{new} = p_{m,n}^{old} + V_{m,n}^{old} \quad (10)$$

Where

$V_{m,n}$ = particle velocity

$P_{m,n}$ = particle variables

C_1, C_2 = positive acceleration constants

r1, r2 = random numbers from uniform distribution

The PSO algorithm updates the velocity vector for each particle then adds that velocity to the particle position or values. Velocity updates are influenced by both the best global solution associated with the lowest cost ever found by a particle and the best local solution associated with the lowest cost in the present population. If the best local solution has a cost less than the cost of the current global solution, then the best local solution replaces the best global solution. The particle velocity is reminiscent of local minimizers that use derivative information, because velocity is the derivative of position. The constant C_1 is called the cognitive parameter. The constant C_2 is called the social parameter. The advantages of PSO are that it is easy to implement and there are few parameters to adjust. The particle swarming becomes evident as the generations pass. The largest group of particles ends up in the vicinity of the global minimum and the next largest group is near the next lowest minimum. A few other particles are roaming the cost surface at some distance away from the two groups. Fig 1. shows plots of $P^{local\ best}_{m,n}$ and $P^{global\ best}_{m,n}$ as well as the population average as a function of generation. The particle $P^{global\ best}_{m,n}$ serves the same function as elite chromosome in the GA. The chaotic swarming process is best illustrated by following the path of one of the particles until it reaches the global minimum. In this implementation the particles frequently bounce off the boundaries.

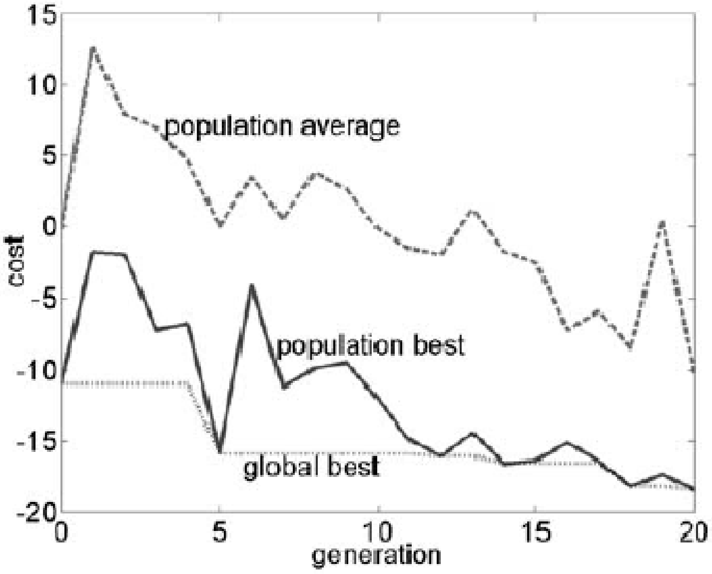

Fig. 1. Convergence of the PSO algorithm

3.2. Node selection using Loss Sensitivity factors

The sensitivity analysis method was used to find the most sensitive candidate for allocating the DG based on loss reduction. The advantage of this method is that it reduces the research space and increases the speed of the evolutionary programming algorithm convergence. The theory behind this method is illustrated in Fig 2.

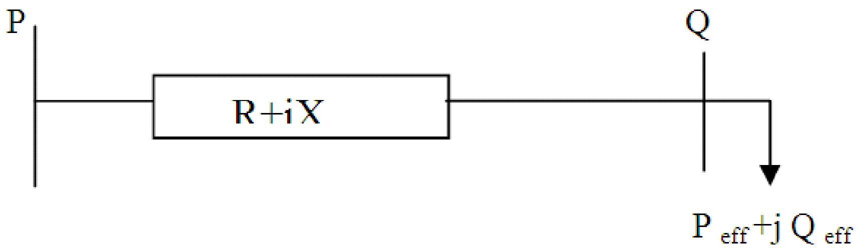

Fig 2. Connected line between bus p and bus q

According of Fig 2, supposing a line with impedance of (R+jX) ohm between bus p and bus q, together with load of $P_{eff} + jQ_{eff}$. The active power losses in Kth line is as (11):

$$P_{line\text{-}loss} = [Ik^2] * R[K] \tag{11}$$

$$I_k = \left(\frac{P_{eff}[q] + jQ_{eff}[q]}{V[q]} \right)^* = \frac{P_{eff}[q] - jQ_{eff}[q]}{V[q]^*} \tag{12}$$

With substituting equation(12) in (11)

$$P_{line\text{-}loss}[q] = \frac{(P_{eff}{}^2[q] + Q_{eff}{}^2[q]\ R[K])}{(V[q]^2)} \tag{13}$$

So, the sensitivity analysis factor is derived by derivative of $P_{line\text{-}loss}$ by P_{eff}, as Equation (14).

$$\frac{\partial P_{line\text{-}loss}}{\partial P_{eff}} = \frac{(2 * P_{eff}[q] * R[K])}{(V[q]^2)} \tag{14}$$

According to equation (14), buses will be ranked and some buses are candidate as the ones which have the most sensitivity for DG placement in order to have the best effect on loss reduction [4]. Generally, the flowchart of process of simulation is as in Fig 3. The algorithm is tested on a 15-bus radial distribution system and IEEE 30bus systems.

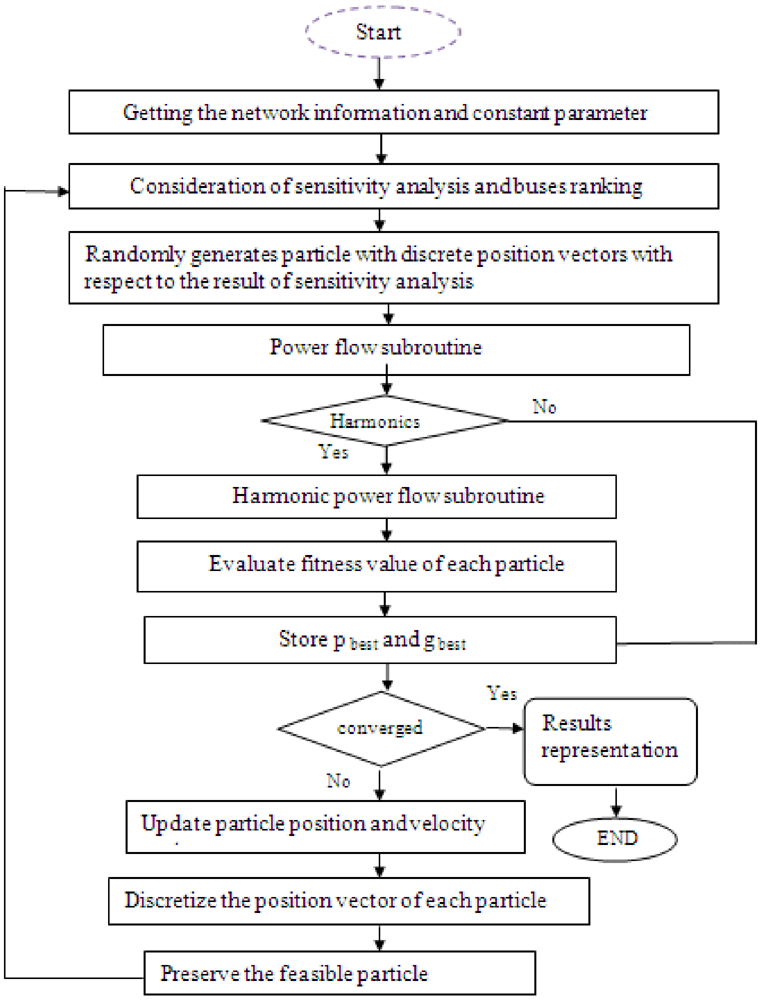

Fig 3. Flowchart of PSO-HP-based algorithm

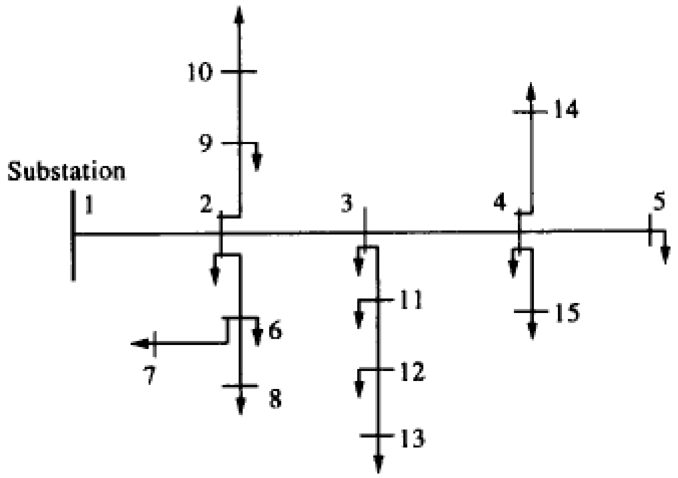

Fig 4. Single line diagram of 15-bus distribution feeder

4. RESULTS AND DISCUSSIONS

The algorithm was tested on 15-bus radial distribution system and IEEE 30 Bus systems. Power factor of the load is taken as $\cos\phi = 0.70$. The system loads are considered as spot ones. The only supply source in the system is the substation at bus 1 as a slack bus with a constant voltage. The maximum number of iterations was taken as 100 for the tuning process of each parameter. To include the presence of harmonics, the PSO was integrated with a harmonic power flow algorithm (HPF). The proposed (PSO-HPF) based approach is tested on the both test systems. For the distorted voltage 15-bus shown in Fig 4 and IEEE 30 bus system shown in Fig 5.Harmonic Producing loads namely fluorescent lighting, adjustable speed drives (ASD), and sources such as PCs, TVs, and etc, are considered [7]. The typical harmonic spectrum of these nonlinear loads is provided as in Table3

Table 1. Line data of 15-bus distribution feeder

Branch no	Sending end node	Receiving end node	R (ohm)	X (ohm)
1	1	2	1.35309	1.32349
2	2	3	1.17024	1.14464
3	3	4	0.84111	0.82271
4	4	5	1.52348	1.02760
5	2	9	2.01317	1.35790
6	9	10	1.68671	1.13770
7	2	6	2.55727	1.72490
8	6	7	1.08820	0.73400
9	6	8	1.25143	0.84410
10	3	11	1.79553	1.21110
11	11	12	2.44845	1.65150

12	12	13	2.01317	1.35790
13	4	14	2.23081	1.50470
14	4	15	1.19702	0.80740

Table 2. Load data of 15 bus distribution feeder

Nodes	KVA	Nodes	KVA
1	0	9	100
2	63	10	63
3	100	11	200
4	200	12	100
5	63	13	63
6	200	14	100
7	200	15	200
8	100		

Table 3. Load composition in terms of harmonic sources

Bus	Harmonic injection current	Order of injected harmonics
2	15%	3
5	15%	3
8	17%	3
10	15%	3
12	17%	3
14	17%	3
15	20%	3

All loads are treated as constant PQ spot loads for harmonic studies. The PSO-HPF-based approach is applied to find the optimal locations and sizes of distributed generations in 15-bus radial distribution system while taking harmonics into account [11]. The total harmonic distortion levels are to be maintained within 5% of the voltage value as recommended by the IEEE standard 519-1992. In the presence of harmonics to investigate the impact of DG installation on total harmonic distortions [2].

Table 4. Voltage profile improvement for 15 bus system

Bus number	Per Unit Voltages at each bus		Bus number	Per Unit Voltages at each bus	
	Without DG	With DG		Without DG	With DG
1	1.0000	1.0000	9	0.9810	0.9843
2	0.9830	0.9862	10	0.9804	0.9836
3	0.9754	0.9801	11	0.9730	0.9786
4	0.9720	0.9773	12	0.9705	0.9762
5	0.9714	0.9767	13	0.9698	0.9754
6	0.9731	0.9788	14	0.9707	0.9760
7	0.9718	0.9775	15	0.9706	0.9759
8	0.9723	0.9780			

Table 5. Results of optimal placement and sizing of DG for 15 bus system

Position of DG Installed with PSO Algorithm	Active Power Injection(MW)
Bus 2	2.44
Bus 4	1.56
Bus 6	1.06

The PSO parameters were tuned to enhance the performance of the proposed algorithm. A swarm size of 200 particles, acceleration constants of 2 and a particle's maximum velocity of 1.5 were selected. From the results shown in Table 5, installing total DGs of 5.06 MW at buses 2, 4 and 6 will reduce the total real power losses from 35.63 kW to25.701 kW. The DG size required to bring the violated bus voltages back within the maximum and minimum bus voltage.

Table 6. Results of sensitivity analysis for 15 bus system

Bus number	Sensitivity to loss reduction	Bus number	Sensitivity to loss reduction
2	0.0153	9	0.0015
6	0.0084	13	0.0009
4	0.0064	5	0.0009
3	0.0054	10	0.0008
7	0.0038	8	0.0008
12	0.0030	11	0.0003
15	0.0018	1	0
14	0.0017		

Table 7. Results of the power losses and THD*v* for 15 bus system

Objectives	Without DG	With DG
Total real power losses	35.63 kW	25.701KW
Average THD*v*	1.634 %	1.36 %

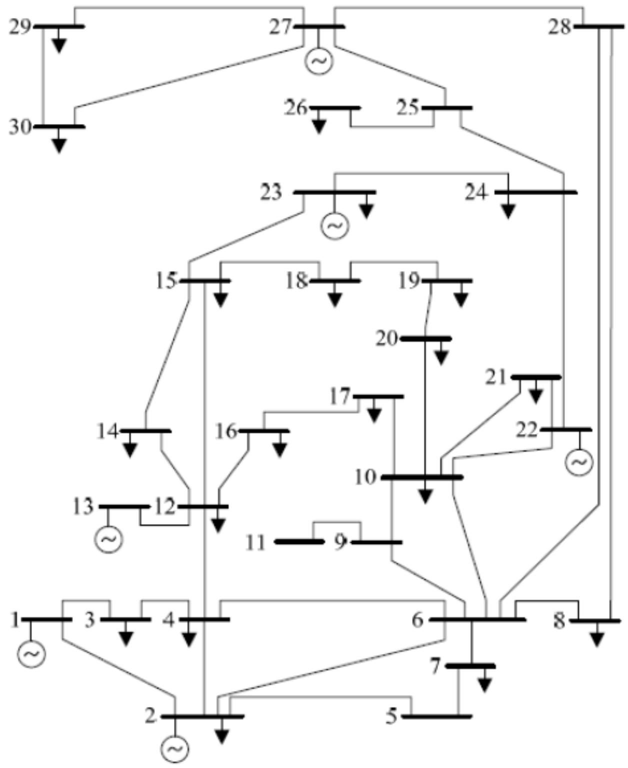

Fig 5. Single line diagram of IEEE 30 Bus system

Table 8. Voltage profile improvement for IEEE 30 Bus system

Bus number	Per Unit Voltages at each bus		Bus number	Per Unit Voltages at each bus	
	Without DG	With DG		Without DG	With DG
1	1.0600	1. 0600	16	1.0244	1.0255
2	1.0330	1. 0330	17	1.0114	1.0126
3	1.0130	1.0163	18	1.0048	1.0061
4	1.0025	1.0050	19	0.9995	1.0008
5	1.0000	1.0000	20	1.0022	1.0035
6	1.0005	1.0016	21	1.0006	1.0025
7	0.9924	0.9931	22	1.0040	1.0053
8	1.0000	1.0000	23	1.0011	1.0029
9	1.0305	1.0314	24	0.9910	0.9924
10	1.0136	1.0148	25	0.9943	0.9954
11	1.0720	1.0720	26	0.9762	0.9773
12	1.0450	1.0461	27	1.0052	1.0060
13	1.0710	1.0710	28	0.9985	0.9994
14	1.0268	1.0279	29	0.9850	0.9858
15	1.0192	1.0206	30	0.9733	0.9741

Table 9. Results of optimal placement and sizing of DG for IEEE 30 Bus system

Position of DG Installed with PSO Algorithm	Active Power Injection(MW)
3	10
4	9.3612
21	2.3961

Table10. Results of sensitivity analysis for IEEE 30 Bus system

Bus number	Sensitivity to loss reduction	Bus number	Sensitivity to loss reduction
6	15.341	10	0.9827
3	10.5819	27	0.9180
4	3.4069	18	0.8702
21	2.8973	24	0.6547
30	2.2801	19	0.6391
28	2.6635	7	0.5656
17	2.1761	23	0.5153
9	1.3483	26	0.2412
22	1.1941	29	0.1481
20	1.0036	25	-0.2507

Table 11. Results of the power losses and THD*v* for IEEE 30Bus system

Objectives	Without DG	With DG
Total real power losses	20.651 kW	18.382 kW
Average THD*v*	1.616%	1.237%

Calculation of capital return is done as below:

Supposing Cost $_{install}$, K_p, K_{ci} as 50, 00, 000 Rs for per DG, 773 Rupee/kW/year and 18, 00, 000 Rupee / kW /year, respectively. K_{ci} is calculated according to average prices of several DGs sizing and then it normalized in order to calculated one kW active power. λ_1 is considered equal to 12. It must be mentioned that to calculation of cost function in one year, term $\lambda_1 K_p P_{loss}$ is multiplied by 8760; total hour of one year. So, with respect to cost function in equation (1) and according to DGs sizing, cost is calculated as follow

Cost=3×500000+5060×1800000+12×773×25.701×8760=1.11 e+10 Rs

Calculation of capital returning is as follow:

$K_i \, Cost_{install} + \sum_i^n K_{ci} P_{inject\text{-}DGi} =$ 3 * 5, 00, 000 + 5060 *1, 800, 000 = 9, 10, 95, 00, 000 Rs

$K_p P_{loss}$(before DG placement)= 8760*773* 35.63=24, 12, 67, 832.4 Rs

$K_p P_{loss}$(after DG placement)= 8760*773* 25.701=17, 40, 33, 807.5 Rs

It is important to mention that. λ_1 isn't calculated above, because it is just a weight coefficient for balancing between the other terms in cost function. Also, DGs placement causes to increase in power transfer capacity in feeder. So, with considering this increasing, it's able to calculate the profit of this power release at the beginning of the feeder. Before DG placement, active power of the beginning of feeder, from bus 1 to bus 2, is 1013.67kW and after DG placement is 904.427 kW. Difference between these two quantities is 109.24 kW. Now, if the price of this power release is considered as, for example, 300 Rs per kW; it means that Distribution Company gains "773-300 = 473 Rs", so the profit of this power release is calculated as follows:

473×109.24×24×365 = 45, 26, 33, 755.2 Rs.

The total cost is calculated as 9, 10, 95, 00, 000 +17, 40, 33, 807.5-45, 26, 33755.2 = 88, 30, 90, 00, 052 Rs. If the quantity of 88, 30, 90, 00, 052 is divided by 24, 12, 67, 832. 4 what is calculated is the number of year for returning investmental cost equals to 3.66 years. It means that with this method of DGs placement and with this sizing, the investmental cost of DG is returned. The summary of these calculations is as Table 12

Table12. Calculation of capital return due to DG installation

	Cost of annual Losses (Rs)	Cost of DGs (Rs)	Annual income of release of power(Rs)	Total cost(Rs)
Before DG installation	2.41e+08	-----	------	2.41e+08
After DG installation	1.74e+08	9.10e+09	4.52e+08	8.83e+10

With respect to Table 12, its clear that after 3.66 years from DGs installation, the total costs are returned. For example, at the 3rd year of DG installation, the profit is equals to

Profit = (35.63-25.701) × 8760 × 773 +109.24 × 8760 × 473 = 51, 98, 67, 780 Rs.

Voltage profile and current of branches before and after DG installation is as Figure 6 and 7, respectively.

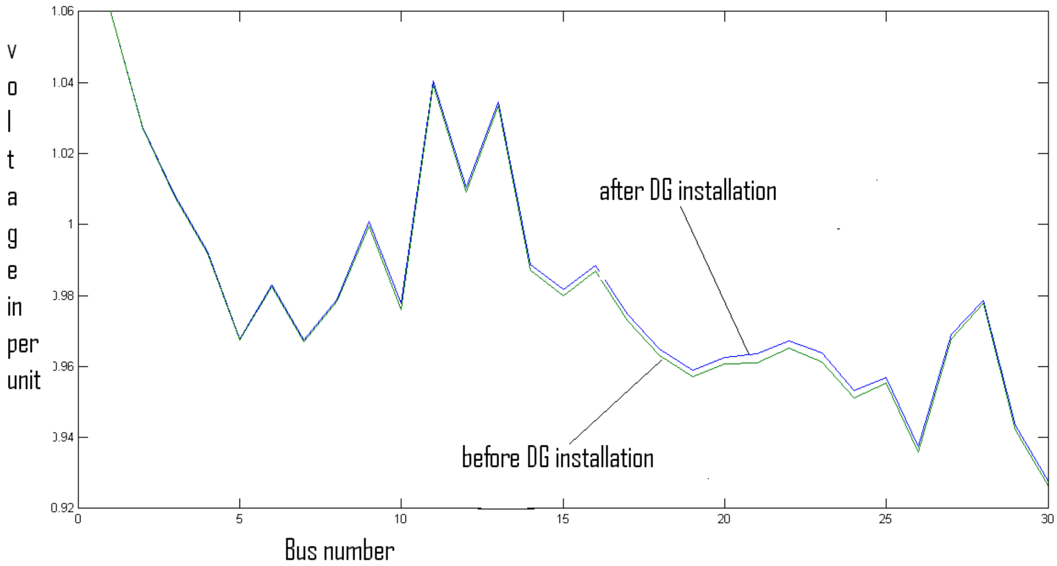

Fig 6. Average of voltage profile before and after DG installation

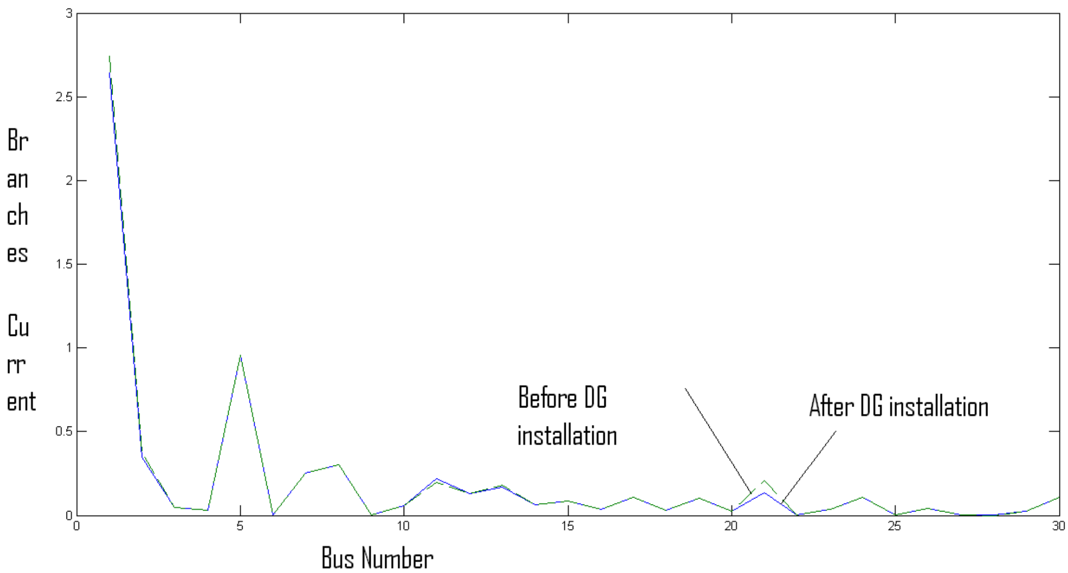

Fig 7. Branches current before and after DG installation

Table 13. Comparison of the proposed method with the existing results

Objectives	Proposed method	Results in [4, 5, 8]
Real power losses	28%	40%
THD*v*	1.67%	3.09%
Cost reduction	27.86%	41%

5. CONCLUSION

In this paper, the PSO algorithm was tested on 15-bus test system and IEEE 30 bus systems to find the optimal locations and sizes of DGs. The multi objective function was to minimize the total power losses, THD*v* and economic cost as well as to improve the voltage profile. The simulation results demonstrate that DG in optimum sizing and sitting can reduce economic cost. In addition, the results indicated that PSO have effectiveness to search optimum point and size of DGs on power system network. Also, improvement of voltage profile, reduction of power losses and an increase in power transfer capacity are results of best DG placement and sizing. The proposed method performed better compared to other methods for minimizing the losses, THD*v and* cost reduction for DG placement.

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[11] Chapter 9: System Studies: "Harmonic Power Flow "by H. H. Zeineldin

BIOGRAPHIES

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