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OPTIMAL DISTRIBUTED GENERATION PLACEMENT AND SIZING FOR LOSS AND THD REDUCTION AND VOLTAGE PROFILE IMPROVEMENT IN DISTRIBUTION SYSTEMS USING PARTICLE SWARM OPTIMIZATION AND SENSITIVITY ANALYSIS

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Abstract- Distributed generations (DGs) play an important role in distribution networks. Among many of their merits, loss and THD reduction and voltage profile improvement can be the salient specifications of DG. Studies show that non-optimal locations and non-optimal sizes of DG units may lead to losses increase, together with bad effect on voltage profile and harmonics. 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. In this optimization method, the investment cost of DGs and power losses are considered in order to being minimized. Firstly, a radial distribution power flow (PF) algorithm is executed to find the global optimal solution. Then, with respect to voltage profile, THD and loss reduction and 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. 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, power losses, optimal placement, Particle Swarm Optimization (PSO), Harmonics.

I. INTRODUCTION

Distributed generation is any electricity generating technology installed by a customer or independent electricity producer that is connected at the distribution system level of the electric grid [1]. It can be said that DG is associated with the use of small generation units located close to or in the load centers. 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.

In addition, 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 [2]. 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 installation of DG units at non-optimal places and with non-optimal sizing can result in an increase in system losses, damaging voltage state, voltage flicker, protection, harmonic, stability and implying in an increase in costs and, therefore, having an effect opposite to the desired [3, 4]. For these reasons, 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 [5], tabu search [6], heuristic algorithms [7, 8] and analytical based methods [9]. The optimum DG allocation can be modeled as optimum active power compensation. DG allocation studies are relatively new, unlike capacitor allocation that has been studied for many years. In [9], analytical method to place DG in radial as well as meshed systems to minimize power loss of the system is presented. In this method separate expressions for radial and network system are derived and a complex procedure based on phasor current is proposed to solve the location problem. However, this 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 test system. The 15-bus test feeder is selected to test proposed method [10]. The results show the best position of DG with minimum economic cost.

II. PROBLEM FORMULATION

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.

- Objective Function: 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

$$F= K_i\, cost_{Install} + \lambda_1 K_P P_{loss} + \sum_i^n K_{ci} P_{inject-DGi} \;\; (Rial) \quad (1)$$

where

K_i	number of DG installed;
$cost_{Install}$	cost of DG installation (Rial);
K_P	annual cost per unit of the real power loss (Rial/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* (Rial/kW/year);
$P_{inject-DGi}$	active power injection at bus *i* (kW);
λ_1	coefficient factor for balancing the prices of $K_P P_{loss}$ with oter terms;

Total real power is defined by

$$Ploss = \sum_{i=1}^{n} Ploss_i \quad \text{(kW)} \qquad (2)$$

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.

- Constraints: Another significant part of the optimization model that needs to be defined is the constraints. There are two types of constraints: equality and inequality.

A. Equality Constraints

These constraints are related to the nonlinear power flow equations. In many published papers, the power flow equations are the real and reactive power mismatch equations. The reason for this is that modified versions of conventional power flow programs such as Newton-Raphson method and Gauss-Siedel method are widely used. In this work, the power flow representation is based on Backward-Forward sweep algorithm [11]. The equality constraints are expressed in a vector form as follows:

$$F\,(x^i, u^i) = 0 \qquad (3)$$

where

x^i	vector of state variables like voltage magnitude;
u^i	vector of DG size;

Be equal to zero of *F*, is associated with satisfying all of the load flow of network.

B. Inequality Constraints

The inequality constraints are those associated with the bus voltages and DG to be installed.

1) Bus Voltage Limits: The bus voltage magnitudes are to be kept within acceptable operating limits throughout the optimization process.

$$V_{min} \le |V_i| \le V_{max} \qquad (4)$$

where

V_{min}	lower bound of bus voltage limits;
V_{max}	upper bound of bus voltage limits;
$\lvert V_i\rvert$	rms value of the bus voltage;

$$|V_i| = \sqrt{\left|V_i^{(1)}\right|^2 + \sum_{h=h_0}^{h_{max}} \left|V_i^{(h)}\right|^2}, \quad i = 2,3, \dots, n \qquad (5)$$

where *n* is number of buses. The rms value of the bus voltage involves only the fundamental component, the first term of (5), when harmonics are not of interest.

2) Total Harmonic Limits: The total harmonic level at each bus is to be kept less or equal to the maximum allowable harmonic level as shown

$$THD_i(\%) \le THD_{max}$$

where THD_{max} is maximum harmonic level at each bus.

3) Number and Sizes of DGs: There are constraints associated with the DGs themselves. DGs that are commercially available come in discrete sizes. That is, the DGs to be dealt with are multiple integers of the smallest capacitor size available and this matter itself is because of coordination between sizes of DGs to be installed with what is available in practical method. This constraint is as follows:

$$P_{inject-DGi} \le LP_0, \quad L=1, 2 \dots n \qquad (6)$$

where P_0 is smallest DG size available. Also, the total active power injection is not to exceed the total active power demand in radial distribution system.

$$\sum_i^n Ploss_i < Ploss_T \qquad (7)$$

where $Ploss_T$ is total active power demand.

III. 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 the GA chromosome). They contain the variable values and are not binary encoded. Each particle moves about the cost surface with a velocity. The particles update their velocities and positions based on the local and global best solutions:

$$V_{m,n}^{new} = V_{m,n}^{old} + \Gamma_1 \times r_1 \times \left(p_{m,n}^{local\ best} - p_{m,n}^{old}\right) + \Gamma_2 \times r_2 \times \left(p_{m,n}^{global\ best} - p_{m,n}^{old}\right) \qquad (8)$$

$$p_{m,n}^{new} = p_{m,n}^{old} + V_{m,n}^{old} \qquad (9)$$

where

$V_{m,n}$	particle velocity
$P_{m,n}$	particle variables
$\Gamma_1 = \Gamma_2$	independent uniform random numbers
$G_1 = G_2$	learning factors = 2
$p_{m,n}^{local\ best}$	best local solution
$p_{m,n}^{global\ best}$	best global solution

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 G_1 is called the cognitive parameter. The constant G_2 is called the social parameter. The advantages of PSO are that it is easy to implement and there are few parameters to adjust [12-16]. Figure 1 shows the initial random swarm set loose on the cost surface. Figure 2 shows the swarm after 5 iterations.

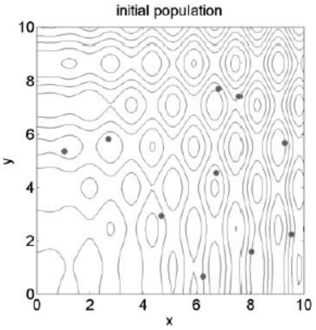

Figure 1. Initial random swarm of 10 particles

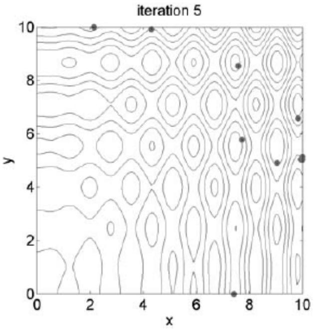

Figure 2. Swarm after 5 iteration

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. Figure 3 shows plots of $p_{m,n}^{local\ best}$ and $p_{m,n}^{global\ best}$ as well as the population average as a function of generation. The particle $p_{m,n}^{global\ best}$ 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 (Figure 3). In this implementation the particles frequently bounce off the boundaries.

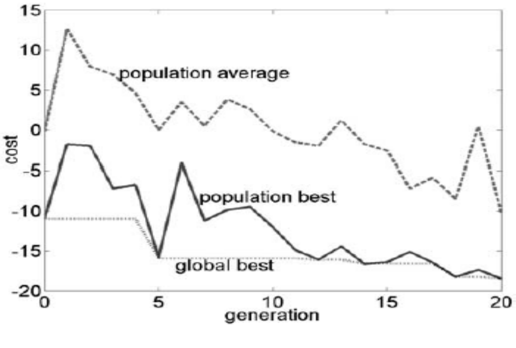

Figure 3. Convergence of the PSO algorithm

IV. NODE SELECTION USING LOSS SENSITIVITY FACTORS

The discrete version of PSO is combined with a three phase power flow backward-forward algorithm. The former is employed as a global optimizer to optimally locate and rate DGs, while the latter is utilized to minimize the power flow equation. The PSO algorithm starts with generating a swarm of particles randomly in the feasible region of the search space.

The feasible swarm is passed to the radial distribution power flow (RDPF) subroutine as initial guess to minimize power flow equations. Each particle recalls its best position associated with the best fitness value (i.e., the total cost). Each particle records the best position achieved by the entire swarm. The update process of particles' positions results in continuous values of particles' positions. Thus, discretization of particles' position vectors is made. Once the updated particles' positions are discredited, the particles go through feasibility check to ensure that no particle flies outside the feasible region [12].

One of techniques that is used in this paper, is the maximum sensitivity analysis in order to candidate some buses for DG placement. The advantages of this method is reducing the research space and increasing the speed of PSO algorithm convergence. Theory of this method is as in Figure 4.

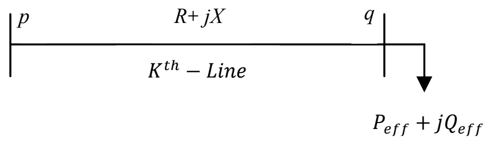

Figure 4. Connected line between bus p and bus q

According of Figure 4, 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 k_{th} line is as (9):

$$P_{Line-loss} = [I_k^2] \times R[k] \tag{9}$$

$$I_k = \left(\frac{P_{eff}[q] + jQ_{eff}[q]}{V[q]}\right)^* = \frac{P_{eff}[q] - jQ_{eff}[q]}{V[q]^*} \tag{10}$$

With substituting equation (10) in (9)

$$P_{Line-loss}[q] = \frac{({P_{eff}}^2[q] + {Q_{eff}}^2[q])R[k]}{(V[q])^2} \tag{11}$$

So, the sensitivity analysis factor is derived by derivative of $P_{Line-loss}$ by P_{eff}, as Equation (12).

$$\frac{\partial P_{Line-loss}}{\partial P_{eff}} = \frac{\left(2 \times P_{eff}[q] \times R[k]\right)}{(V[q])^2} \tag{12}$$

According to equation (12), 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. Generally, the flowchart of process of simulation is as Figure 5. The algorithm is tested on a 15-bus radial distribution system as Figure 6 [10]. Characteristics of this distribution feeder are as Tables 1 and 2.

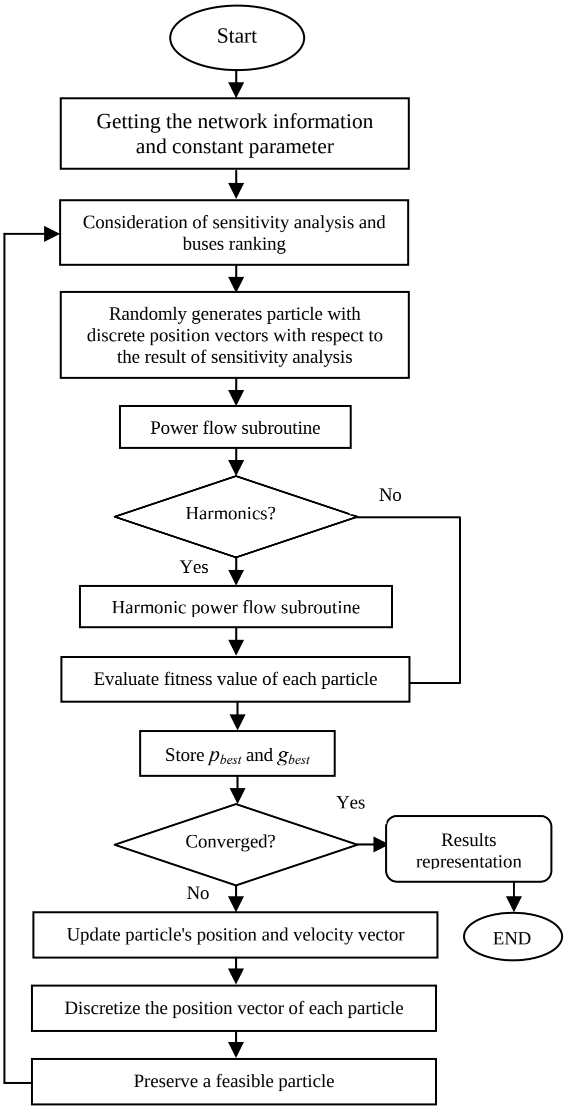

Figure 5. Flowchart of the PSO-HP-based algorithm simulation

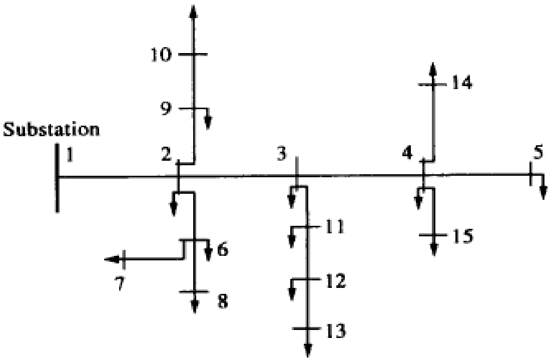

Figure 6. Single line diagram of 15-bus distribution feeder

V. RESULTS AND DISCUSSIONS

The algorithm was tested on a 15-bus radial distribution system. Power factor of the load is taken as cosφ = 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 same test system (15-bus). For the distorted voltage 15-bus shown in Figure 6, harmonic-producing loads, namely fluorescent lighting, adjustable speed drives (ASD), and sources such as PCs, TVs, and etc, are considered [17]. The typical harmonic spectrum of these nonlinear loads is provided as Table 3.

Table 1. Line data of 15-bus distribution feeder

Branch number	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 buses 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 harmonic
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 shunt capacitors in 15-bus radial distribution system while taking harmonics into account. 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, three different cases are considered to investigate the impact of DG installation on total harmonic distortions.

- **Case 1** represents the system with harmonics consideration before DG installation.
- **Case 2** represents the system with harmonics consideration after DG installation.

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 4, installing total DGs of 650 kW at buses 6, 11 and 15 will reduce the total real power losses from 61.7944 kW to 36.5502 kW. The DG size required to bring the violated bus voltages back within the maximum and minimum bus voltage.

Table 4. Results of optimal placement and sizing of DG

Position of DG Installed with PSO Algorithm	Active Power Injection (kW)
Bus 6	200
Bus 11	250
Bus 15	200

Results of total harmonic distortion of 15-bus radial distribution system are given in Table 6. The advantages of sensitivity analysis as mentioned is reducing the search space of PSO and consequently increasing the speed of simulation. Without this analysis, it's necessary to import all of the buses in PSO algorithm to find the best placement of DGs. The result of executing sensitivity analysis is as Table 5.

Table 5. Results of sensitivity analysis

Sensitivity to loss reduction	Bus number
0.0291	2
0.0161	6
0.0152	3
0.0084	11
0.0061	4
0.0052	12
0.0041	9
0.0031	15
0.0029	14
0.0028	7
0.0016	13
0.0016	8
0.0013	10
0.0012	5

As is shown in Table 4, giving the buses of 2, 6, 3, 11, 4, 12, 9, 15 and 14 to PSO algorithm is sufficient to calculate the best placement and sizing among them. On the other words, if all of the buses are given to PSO algorithm, the answer is as same as the sensitivity algorithm. In Table 7, total results of system before and after DG placement are shown. It can be seen that presence of installed DGs causes to decrease the THD of system.

Calculation of capital return is done as below:

Supposing $cost_{Install}$, K_P, K_{ci} as 5,000,000 Rials for per DG, 773 Rial/kW/year and 1,800,000 Rial/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:

Table 6. Results of total harmonic distortion

Bus number	Case 1	Case 2
	THD (%)	THD (%)
1	0	0
2	3/2512	2/3401
3	3/1296	2/5515
4	3/1446	2/1220
5	3/2512	2/3401
6	3/0541	2/1560
7	2/6594	1/9910
8	4/1299	3/2001
9	3/9541	2/9666
10	3/2512	2/3401
11	3/1201	2/5212
12	4/1299	3/2001
13	3/6519	2/4556
14	4/1299	3/2001
15	4/7443	3/2115

Table 7. Results before and after DG placement

	Before DG placement	After DG placement
Input Active Power, P_{in}(kW)	1288.2	1263.00
Input Reactive Power, Q_{in} (kVAR)	1308.5	634.9468
Output Active Power, P_{out}(kW)	1226.4	1226.4
Output Reactive Power, Q_{out}(kVAR)	1251.2	601.1783
Active Power Losses, P_{loss} (kW)	61.7944	36.5502
Reactive Power Losses, Q_{loss} (kVAR)	57.2977	33.7686
Percentage of P_{loss}	4.7970	2.8940
Power Factor	0.7016	0.8934
Minimum Bus Voltage (p.u)	0.9445	0.9632
Maximum Bus Voltage (p.u)	0.9713	0.9887
Input Current of Feeder, I_{branch} (A)	96.3744	74.1936

Cost=3×500000+650×1800000+12×773×35.5502×8760= 415497112.8 Rials

Calculation of capital returning is as follow:

$K_i\ cost_{Install} + \sum_i^n K_{ci} P_{inject-DGi} = 3 \times 5{,}00{,}000 + 650 \times 1{,}800{,}000 = 1{,}185{,}000{,}000\ Rials$

$K_P P_{loss}(before\ DG\ placeme = 8760 \times 773 \times 61.794 =$ 418,439,543.7 Rials

$K_P P_{loss}(after\ DG\ placement) = 8760 \times 773 \times 36.5502\ =$ 247,498,948.3 Rials

It is important to mention that λ_1 isn't calculated in part a, 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 that is shown in Table 7. 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 1288.2 kW and after DG placement is 1263 kW. Difference between these two quantities is 25.2 kW. Now, if the price of this power release is considered as, for example, 300 Rials per kW; it means that Distribution Company gains "773-300 = 473 Rials", so the profit of this power release is calculated as follow:

473×25.2×24×365=104,415,696 Rials

The total cost is calculated as "1,185,000,000 + 247,498,948.3 - 104,415,696 = 1,328,083,252 Rials". If the quantity of 1,328,083,252 is divided by 418,439,543.7 what is calculated is the number of year for returning investmental cost equals to 3.17 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 8:

Table 8. Calculation of capital return due to DG installation

	Cost of annual losses (Rial)	Cost of DGs (Rial)	Annual income of release of power (Rial)	Total cost (Rial)
Before DG installation	418,439,543	-	-	418,439,543
After DG installation	247,498,948	1,185,000,000	104,415,696	1,328,083,252

With respect to Table 8, its clear that after 3.17 years from DGs installation, the total costs are returned. For example, at the 4th year of DG installation, the profit is equals to

Profit = (61.7944 - 36.5502) × 8760 × 773 +
25.2 × 8760 × 473 = 275356291.4 Rials

Table 9. Current of branches before and after DG placement

Branches name	Current before DG placement (A)	Current after DG placement (A)
1 – 2	96.3744	74.1936
2 – 3	56.7080	42.0513
3 – 4	31.1212	24.1286
4 – 5	3.4810	3.4312
2 – 9	8.8422	8.7723
9 – 10	3.4198	3.3928
2 – 6	27.4199	20.8115
6 – 7	10.9803	10.8578
6 – 8	5.4847	5.4237
3 – 11	20.1005	13.8671
11 – 12	9.0501	8.9083
12 – 13	3.5009	3.4459
4 - 14	5.5330	5.4536
4 - 15	11.0679	8.2367

Voltage profile and current of branches before and after DG installation is as Figure 7 and 8, respectively. Figure 9 indicates the convergence speed of the proposed PSO based solution methodology in finding the global optimal solution of the DG allocation and sizing problem.

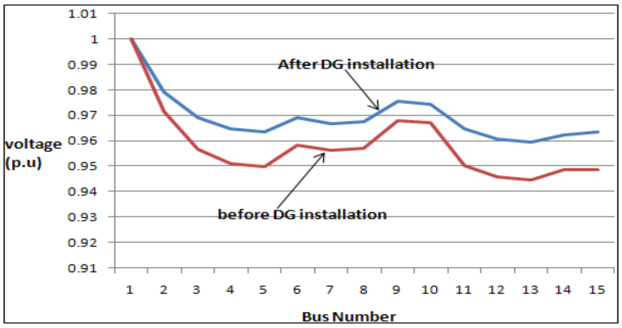

Figure 7. Average of voltage profile before and after DG installation

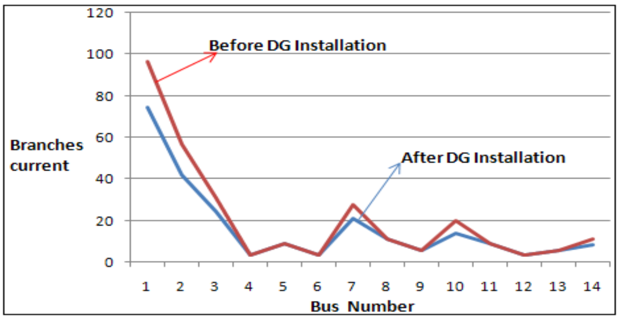

Figure 8. Branches current before and after DG installation

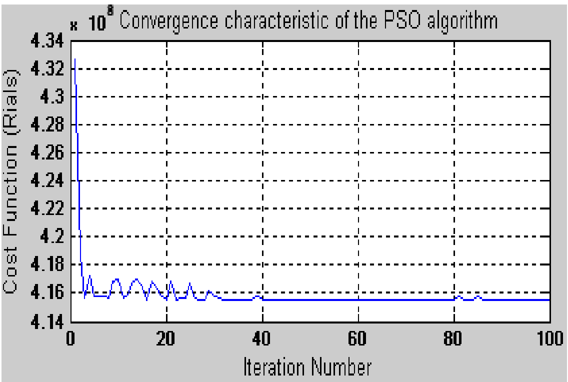

Figure 9. Convergence characteristic of PSO algorithm

V. CONCLUSIONS

In this paper, the PSO algorithm was tested on a 15-bus test system to find the optimal locations and sizes of DGs. The objective was to minimize the total cost of the system, real power loss and the number of DGs to be installed. The objective function was subject to some operating constraints. The simulation results demonstrate that DG in optimum sizing and sitting can reduce economic cost. The number of DGs effect goodly to reduce economic cost. In addition, the result 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 result of best DG placement and sizing.

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