Application of Particle Swarm Optimization for Solving Optimal Generation Plant Location Problem

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***Abstract*—The global demand for energy especially in developing countries, has been witnessing a tremendous growth due to rapid population growth, economic growth and developing industrial sectors. Therefore, it is necessary to forecast the future energy needs and expand generation capacity to meet the increasing peak demand. This paper presents an optimization approach to determine the optimal location for installing a new generator in which the technical, economic and environmental aspects are all taken into consideration. The location that yields the minimum fuel costs, total emission and system loss is considered as the optimal generation plant location. The formulated objective function and its constraints compose an optimization problem is solved using particle swarm optimization (PSO). The proposed PSO based optimization approach is tested on IEEE 14-bus system and IEEE 30-bus system to illustrate the potential of the new approach. The simulation results have shown that the proposed approach is indeed capable of determining the optimal generation location that can save much overall fuel cost as well as reduce the total emissions of generators and losses in the network.**

***Index Terms*—Generation expansion planning, optimal location, particle swarm optimization.**

I. INTRODUCTION

THE global demand for energy especially in developing countries, has been witnessing at remendous growth due to rapid population growth, economic growth, improving social life, urbanization and developing industrial sectors. The expansion of power generation capacity is the solution to meet the ever-increasing consumer demand for energy. Expanding the power generation capacity can be done either by augmenting the existing plant or setting up new plant at new location [1]. However, addition of new generating units to an existing power network has significant impacts on the price of electricity production, the congestion conditions in the network and the efficiency of electricity generation, depending on where the new units will be installed. Hence, the location of generation plants is a very important factor and must be taken into consideration in developing plan for the expansion of power generation capacity.

Besides the technical and economic factors of locating the plant, another issue relevant to consider is the environmental impact. Major part of the electricity production in the world is generated from non-renewable sources such as coal, gas and oil. These fossil fuel power plants produce polluting gaseous such as sulphur dioxide (SO_2), nitrogen oxide (NO_X) and carbon dioxide (CO_2). Their emission contribution cannot be neglected. Recently, the increasing public awareness of the environmental protection has forced the utilities to modify their operational strategies to reduce pollution and environmental emissions of the thermal power plants [2]. For these reasons, a study is carried out to develop a methodology which is capable of identifying the location of a new generation plant that can provide economic, technical and environmental

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advantages. The economic advantages are saving of total fuel cost. Environmental advantages entail reductions of gaseous emission produced by power plants. Technical advantages cover transmission system benefit, like system loss reduction and alleviate transmission congestion. In this paper, an optimization approach minimizing total fuel cost with minimal impacts on environment subject to physical and technological constraints by using PSO technique has been proposed to determine the suitable location of a new generation plant for a given system. The proposed approach can be very useful for an electric utility with a central planning organization when dealing with capacity expansion investment.

The problem of determining the location of new generation has been addressed in the literature. The authors in [3] proposed a concept of T-index which is based on the relative electrical distance between the generator and the load locations, for ranking the most significant new generation locations and indicates the amount of permissible generations that can be installed at the new locations. However, this method neglects the local load when placing a new generator on the same bus. The issues related to the effect of the location of the new unit on the profit of generating firm are discussed in [4] from the perspective of competitive electricity market. The impacts on the social welfare, nodal prices, bidding strategies and power distribution in the network are also discussed. In [5], a generating capacity expansion model focusing on the problem of generation plant location optimization have been developed in which the capacity of power transmission lines, the investment and operation cost are all taken into considerations. However, from a practical viewpoint, the results of the proposed algorithms cannot guarantee the cost saving. Discussions related to some of the generation expansion planning (GEP) issues have been presented in [6]-[8]. Briefly stated, the expansion planning of generating system includes decisions such as generation plant capacity, types of plant, time of introductions and locations. Most models attempt to solve the GEP problems in which the location of generation plant being the usual exception. Recently, applications of meta-heuristic optimization technique such as PSO has attracted a lot of attention for solving various optimization problems in power system area like optimal power flow [9],[10], distributed generation location [11]-[13], and others. This technique is capable of solving complex optimization problems such as those with a non-continuous, non-convex and highly nonlinear solution space. Many different classical optimization techniques such as linear programming, nonlinear programming, Newton-based techniques, quadratic programming and interior point methods suffer from poor convergence characteristics and difficulties to search for global solutions. [14]

The remainder of this paper is organized as follows. The mathematical formulation of the objective function and constraints of the optimization problem are described in Section II. In Section III, the overview of PSO technique as an optimization tool employed in this paper is explained. The proposed methodology implemented in this paper is presented in Section IV. In Section V, the case studies applied in this paper is provided including illustrative numerical results and discussions. Finally, Section VI summarizes the main findings of the paper.

II. PROBLEM FORMULATION

A general constrained non-linear multi-objective optimization problem considering fuel cost and emission function of all generators in the system has been formulated to find the optimal generation location.

$$\text{Minimize } [F(P_G), E(P_G)] \tag{1}$$

$$\text{Subject to: } g(P_G) = 0 \tag{2}$$

$$h(P_G) \leq 0 \tag{3}$$

where g is the equality constraint representing the power balance, while h is the inequality constraint representing the generation capacity and power system security.

The total fuel cost of the generators, $F(P_G)$ (\$/h) and the total emission of power generation, $E(P_G)$ (kg/h), can be expressed by a quadratic function of real power generation as follows:

$$F(P_G) = \sum_{i=1}^{N_g} a_i P_{Gi}^2 + b_i P_{Gi} + c_i \tag{4}$$

$$E(P_G) = \sum_{i=1}^{N_g} d_i P_{Gi}^2 + e_i P_{Gi} + f_i \tag{5}$$

where,

a_i, b_i, c_i cost coefficients of generating unit i

d_i, e_i, f_i emission coefficients of generating unit i

P_{Gi} real power generation at bus i

N_g number of generators in the system

The multi-objective optimization problem is converted to a single optimization problem by introducing a price penalty factor h (\$/kg) as follows:

$$\text{Minimize } f = F(P_G) + hE(P_G) \tag{6}$$

where h is the ratio between the fuel cost and emission of each generator at its maximum power capacity h can be calculated as follows:

$$h_i = \frac{F_i(P_{Gi}^{\max})}{E_i(P_{Gi}^{\max})} \quad i = 1, \ldots, N_g \tag{7}$$

The insertion of the price penalty factor h in the function has defined that, the total operating cost of the system is the cost of fuel plus the implied cost of emission. The maximum price penalty factor has been selected for combining cost of fuel plus the implied cost of emission as it offers a very good solution for emission restricted fewer cost conditions [15].

This objective function is subjected to the following constraints.

A. Equality constraints

Power balance equations: It is necessary to ensure the output of generators serve the total load demand P_D and total losses in transmission lines P_{Loss}. Hence:

$$\sum_{i=1}^{N_g} P_{Gi} - P_D - P_{Loss} = 0 \tag{8}$$

As a matter of fact, the calculation of the system loss can be done by different methods such as B-coefficients method or general loss formula. In this paper, power flow method has been employed for loss calculation corresponding to both real and reactive power balance equation as follows:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{N_b} V_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)] = 0 \tag{9}$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{N_b} V_j [G_{ij} \cos(\delta_i - \delta_j) - B_{ij} \sin(\delta_i - \delta_j)] = 0 \tag{10}$$

where,

P_{Di}, Q_{Di} real and reactive power demand at bus i

Q_{Gi} reactive power generation at bus i

G_{ij} transfer conductance between bus i and j

B_{ij} transfer susceptance between bus i and j

V_i, V_j voltage magnitude at bus i and j

δ_i, δ_j voltage angle at bus i and j

N_b number of buses in the system

B. Inequality constraints

1) Power generation limit: For stable operation, the real output of each generator is restricted by lower and upper limits as follows:

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max}, \quad i = 1, \ldots, N_g \tag{11}$$

where P_{Gi}^{min} and P_{Gi}^{max} are minimum and maximum output of the generator i respectively.

2) Voltage limit: This includes the upper and lower bounds of the voltage magnitude at all buses. The voltage limit at bus i can be written as:

$$V_i^{min} \leq V_i \leq V_i^{max}, \quad i = 1, \ldots, N_b \tag{12}$$

where V_i^{min} and V_i^{max} are, respectively, minimum and maximum voltage at bus i.

3) Line flow limit: For secure operation, the transmission line loading is restricted by its maximum line flow in a transmission line based on the thermal and stability considerations. The line flow limit can be written as:

$$|P_l| \leq P_l^{max}, \quad l = 1, \ldots, N_l \tag{13}$$

where P_l is the transmission line loading and N_l is the total number of transmission lines.

III. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) is a population-based search algorithm and searches in parallel using a group of particles proposed by Kennedy and Eberhart in 1995 [16]. Kennedy and Eberhart developed the original PSO based on the analogy of swarm of bird and school of fish. PSO is initialized with a group of random particles and then searches for optima by updating generations. Each particle in PSO changes its position with time and moves to optimum position. Another characteristic in the PSO method is called swarm. A swarm includes a set of particles, neighbouring the particle and its history experience. Each particle in PSO makes its decision using its own experience and its neighbour's experiences for evolution. That is, particles approach to the optimum through its present velocity, previous experience, and the best experience of its neighbours.

The main advantages of PSO compared to other optimization techniques are as follows [17]:

1) Coding implementation in PSO is easy.
2) PSO has stable convergence characteristics of PSO.
3) PSO has very fewer parameters to adjust.
4) PSO is less sensitive to the nature of objective function.
5) PSO is very efficient in performing a global search.
6) PSO can obtain high quality solutions within shorter calculation time.

Variable x and v are regarded as vectors that show various positions and velocities of particle. Thus, the position and velocity of particle-i in a physical n-dimensional search space are represented as:

$$X_i = (x_{i1}, x_{i2}, \dots, x_{i3}) \tag{14}$$

$$V_i = (v_{i1}, v_{i2}, \dots, v_{i3}) \tag{15}$$

In order to reach to optimum position, the best position of particle i and its neighbours' best position are recorded as:

$$Pbest_i = (Pbest_{i1}, Pbest_{i2}, \dots, Pbest_{i3}) \tag{16}$$

$$Gbest_i = (Gbest_{i1}, Gbest_{i2}, \dots, Gbest_{i3}) \tag{17}$$

To search the better velocity and position of each particle, the modified velocity and position in the next iteration can be calculated as follows:

$$V_i^{k+1} = \omega V_i^k + c_1 r_1 \times \left(Pbest_i^k - X_i^k\right) + c_2 r_2 \times (Gbest^k - X_i^k) \tag{18}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{19}$$

where,

V_i^k velocity of particle i at iteration k

ω inertia weight factor

c_1, c_2 acceleration coefficients

r_1, r_2 random numbers between 0 and 1

X_i^k position of particle i at iteration k

$Pbest_i^k$ best position of particle i at until iteration k

$Gbest^k$ best position of the groupat until iteration k

Fig. 1 shows the position mechanism of standard PSO in two dimensions.

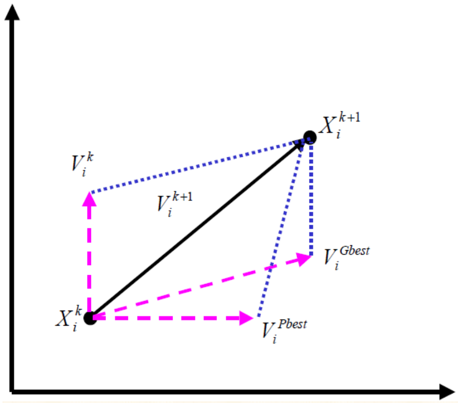

Fig. 1. Updating the position mechanism of PSO

In the updating process, the values of parameters such asc_1, c_2 and ω should be determined beforehand. Low values of c_1 and c_2 allow particles to roam far from the target regions before being tugged back. On the other hand, high values result in abrupt movement toward, or past target regions. Hence, the values ofc_1 and $c_2$were often set to be 2 according to past experiences. As for ω, suitable selection of the weight can provide a balance between global and local explorations. In general, the weight ω is set according to the following equation:

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{iter_{\max}} \times iter \tag{20}$$

where,

$\omega_{max}, \omega_{min}$ initial, final weights

$iter_{max}$ maximum iteration number

$iter$ current iteration number

IV. Proposed Methodology

To meet the increasing load demand, addition of a new generation plant is necessary. Before installing a new generator, it is important to identify the most suitable location to place the generator. In this section, a methodology is proposed to find the optimal location of the generator which will give the lowest possible total fuel cost, emission and system losses. First, all the possible locations are examined and a new generator is located at each bus of the test system successively to model the generation unit installation in a system. The next step is to solve the optimization problem using PSO. PSO has the task to search the possible lowest total fuel cost, emission and line losses in the system. A Newton-Raphson algorithm based AC load flow program is used to solve the load flow problem. The procedure is then repeated by placing the new generator with the remaining buses in the system. Finally the results obtained by placing the generator at each bus will be compared and the corresponding bus location with the best results is considered as the optimal location to install the new generator. Fig. 2 shows the detailed computational flow to depict the proposed methodology.

In order to better clarify, the PSO algorithm applied to the optimization in the proposed methodology problem can be described as follows:

Step 1: Input parameters of the system and specify the lower and upper boundaries of each variable.

Step 2: Randomly generates the initial particles of the population over the problem space.

Step 3: For each particle, run AC load flow method to compute the objective of each solution.

Step 4: Compare the objective function of each particle with its Pbest. If the current value is better than Pbest then set Pbest value equal to the current value and set Pbest position to the current position.

Step 5: If the current fitness value is better than the Gbest, then update Gbest to current best position and fitness value.

Step 6: Update the velocity and position of each particle according to equation (18) and (19) respectively.

Step 7: Repeat Step 3 to 6 is repeated until the convergence criterion of the maximum number of evaluations is met. Corresponding to optimal generation output, calculate fuel cost and total emission.

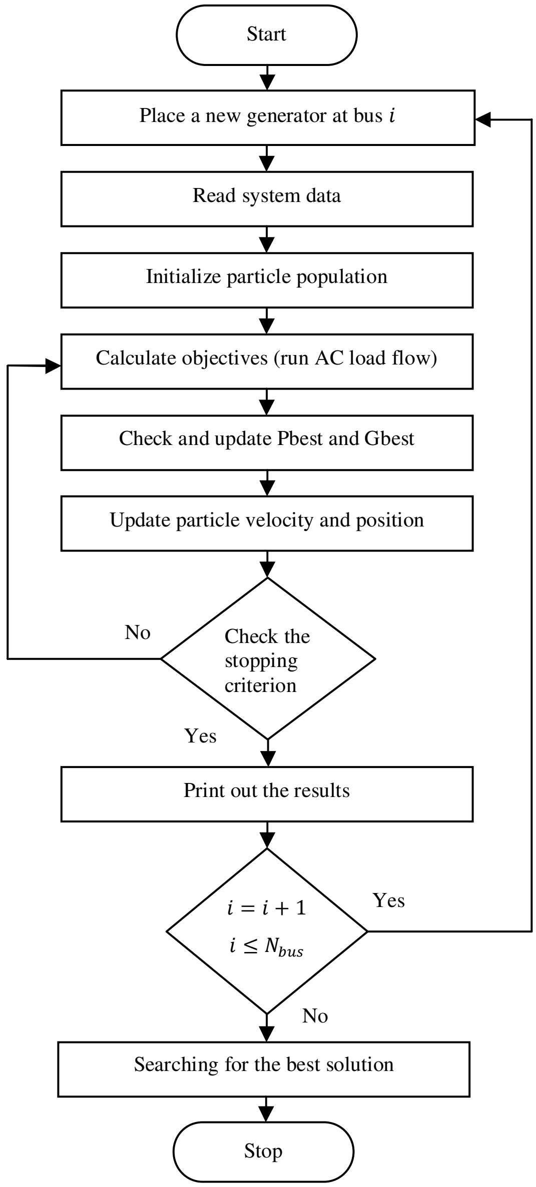

Fig. 2.Computational flow of the proposed methodology

V. Simulation Results and Discussions

The proposed methodology in this paper has been tested on two different test bus systems to demonstrate the applicability of the proposed methodology to find the optimal generation plant location. A computer program has been written in MATLAB platform to run the proposed methodology. In all optimization runs, the parameter settings to execute PSO are, population size=20, maximum generation= 300.

A) IEEE 14-bus system

In this section, the modified IEEE 14-bus system is used to test the proposed methodology in finding the optimal location of the new generator in the system. Briefly, the system consists of 14 buses, 5 existing generators and 11 loads as shown in Fig. 3. The line and load data are given in [18]. In this case, each load is uniformly increased by 10%, and the new total load demand is 336.7MW. It is assumed that the 10% increased load cannot be met by the maximum capacities of the existing generators. In such a situation, generation expansion is necessary. Therefore, a new generator with 100MW capacity will be added to the system to meet the projected load growth. The parameters of the generators including the new generator are shown in Appendix. The obtained fuel cost, total emission and system loss with the new generator at each bus in the system are shown in Table1. Fig. 4 shows graphically the comparison of results obtained for all bus locations. For each system, the optimal location can be determined directly from the comparison figures.

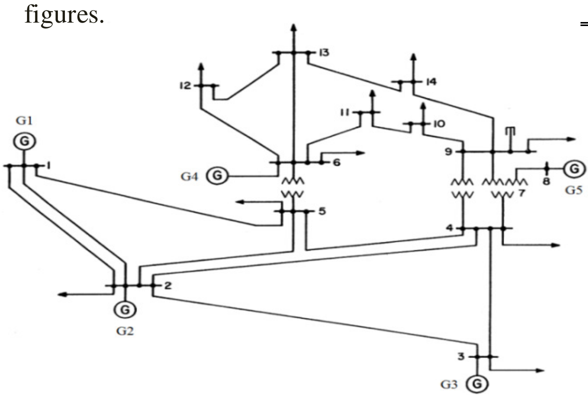

Fig. 3. IEEE 14-bus system

Based on the results in Table 1, it is revealed that different fuel cost, total emission and system loss pattern are obtained while locating the new generator at different buses. It can be observed that locating the new generator at bus 6 has the lowest fuel cost, total emission and system loss compared to all other bus locations. Hence, it is chosen as the most suitable location for placing the new generation plant. Besides, this location is best suited as there will not arise any problem of transmission congestion, even without adding additional transmission lines. On the other hand, it can be observed that bus 1 and 12 are relatively poor locations for the new generation plant. Locating the new generator at these buses yield very high fuel cost, total emission and system loss.

TABLE 1
SIMULATION RESULTS WITH NEW GENERATOR LOCATED AT EACH BUS FOR IEEE 14-BUS SYSTEM

Bus location	Fuel cost ($/h)	Total emission (kg/h)	System loss (MW)
1	15592.27	313.7129	14.8418
2	15553.60	312.9973	13.5200
3	15476.64	311.9939	11.1642
4	15479.89	311.9324	11.1434
5	15490.56	312.0567	11.4620
6	15304.02	309.7104	5.4554
7	15470.87	311.8256	10.8620
8	15455.43	311.6256	10.3594
9	15473.03	311.8636	10.9406
10	15492.89	312.1437	11.5853
11	15531.21	312.7164	12.7988
12	15578.12	313.7115	14.2513
13	15504.70	312.3393	11.9246
14	15503.71	312.4274	11.9276

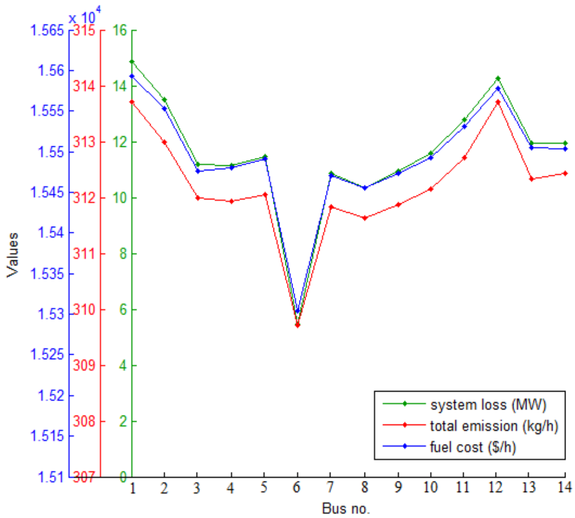

Fig. 4. Variation of simulation results for IEEE 14-bus system

B) *IEEE 30-bus system*

The results have been obtained for IEEE 30-bus system as well. The single line diagram of the 30-bus system is given in Fig. 5. The system consists of 30 buses, 6 existing generators and 21 loads. The system load and line data are given in [18].

The parameters of the generators are given in Appendix. The peak load to be met after 10% load increased is 369.42MW. To meet the projected load growth, a new generator is added to the system. For this case, the simulation results are shown in Table II. Fig. 6 illustrates the variation of the simulation results.

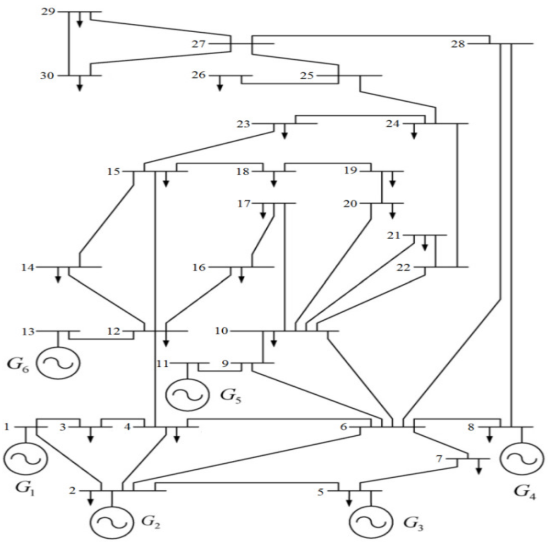

Fig. 3. IEEE 14-bus system

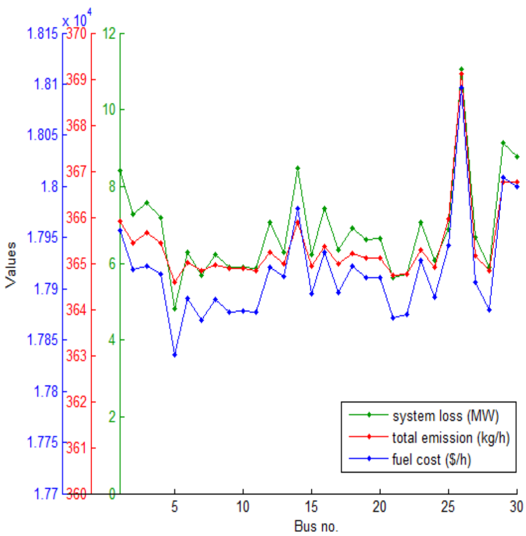

Fig. 6. Variation of simulation results for IEEE 30-bus system

TABLE II
Simulation Results with New Generator Located at Each Bus for IEEE 30-Bus System

Bus location	Fuel cost ($/h)	Total emission (kg/h)	System loss (MW)
1	17957.45	365.9049	8.4056
2	17919.20	365.4370	7.2649
3	17922.40	365.6525	7.5618
4	17914.02	365.4373	7.1845
5	17835.87	364.5833	4.8189
6	17890.42	365.0085	6.2757
7	17869.35	364.8318	5.7000
8	17889.82	364.9651	6.2295
9	17877.18	364.8777	5.8811
10	17877.78	364.8810	5.8971
11	17877.72	364.8444	5.8714
12	17920.51	365.2258	7.0611
13	17912.21	364.9988	6.2940
14	17978.54	365.8943	8.4786
15	17895.17	364.9276	6.2262
16	17935.43	365.3602	7.4198
17	17896.61	364.9816	6.3535
18	17922.08	365.2212	6.9103
19	17911.36	365.1076	6.6190
20	17910.53	365.1008	6.6371
21	17871.77	364.7370	5.6155
22	17875.48	364.7715	5.7221
23	17927.83	365.2987	7.0616
24	17891.46	364.9091	6.0645
25	17942.78	365.9696	6.8814
26	18096.44	369.1167	11.0468
27	17906.12	365.1619	6.6650
28	17879.14	364.8347	5.8859
29	18008.34	366.7679	9.1336
30	17999.34	366.7692	8.7652

For the IEEE 30-bus system, the lowest fuel cost, total emission and system loss are obtained when locating the new generator at bus 5 as shown in Table 2 and Fig. 6. Installing the new generator at bus 5 is most preferable compared to all other bus locations in the system. Hence, bus 5 is considered as the optimal location for the new generation plant. On the contrary, it is not beneficial to install the new generator at bus 26 due to very high fuel cost, total emission and system loss obtained while locating the new generator at these buses.

For comparison purposes, genetic algorithm (GA) is applied to solve both case studies. The performance and effectiveness of PSO are compared with GA in terms of the simulation results and the average computational time. For implementing GA, population size of 20 is taken and the maximum number of generations is taken as 300. The comparisons are tabulated in Table III. In addition, the PSO and GA convergence characteristics for IEEE 14-bus system are depicted in Fig. 7.

TABLE III
COMPARISON OF THE BEST RESULTS OBTAINED BY PSO AND GA

Method	Fuel cost ($/h)	Total emission (Kg/h)	System loss (MW)	CPU time (s)
IEEE 14-bus system				
PSO	15304.02	309.7104	5.4554	19.20
GA	15306.05	309.8959	5.6651	24.92
IEEE 30-bus system				
PSO	17835.87	364.5833	4.8189	44.47
GA	17853.56	367.1067	4.9125	50.29

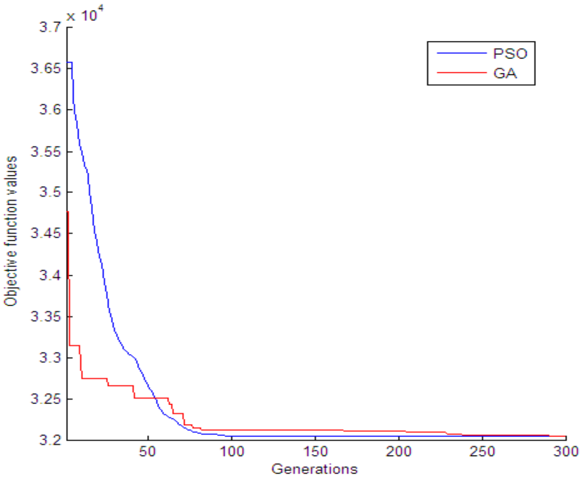

Fig. 7. Convergence characteristics of PSO and GA for IEEE 14-bus system

From Table III, it is quite evident that the proposed PSO based approach outperforms GA for both cases. PSO always obtains less total fuel cost, emission and system loss than GA. For average computational time, PSO is faster than GA for both cases. Therefore, PSO is more efficient than GA in solving the problem for both systems. Fig. 7 proves that PSO technique has a stable and faster convergence characteristic than GA. The fast convergence of the PSO technique shows that it takes only few generations to reach the optimal solution compared to GA. It is clearly shown that there is no rapid change in the objective function value after 100 generations for PSO, while GA fails to converge to the local optimum value in 100 generations.

VI. CONCLUSION

In this paper, the optimal generation plant location has been successfully determined using a proposed PSO based approach, for a given network. The problem has been formulated with fuel cost and emission objectives and is subjected to a number of constraints. The optimal generation plant location is chosen based on minimum fuel cost, total emission and total line losses of the system. Case studies are carried out on IEEE 14-bus and IEEE 30-bus system considering future projected load. The patterns of fuel cost, total emission and system losses have been obtained with new generator located at each bus. The simulation results show that the optimal generation plant location can save much overall fuel cost as well as reduce the total emissions of generators and losses in the network. Besides, the proposed method ensures the addition of new capacity can be done without any problem of transmission line congestion. This could save the investment and operation cost of network expansion. Therefore, for better long term operational benefits of the power system, it is essential to locate the new generation plant at an optimal location. The simulation results are also compared with other optimization technique to illustrate the effectiveness of the PSO based proposed approach. The results show that PSO can obtain better optimal solutions in a fast computing manner. Hence, PSO is a favorable technique for solving the problem.

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APPENDIX

Generator fuel cost coefficients

	a	*b*	*c*
	IEEE 14-bus system		
G1	0.0301	27.5	750
G2	0.0195	27.3	1400
G3	0.0203	30.0	1050
G4	0.0507	26.5	450
G5	0.0400	28.0	600
Gnew	0.0264	27.5	950
	IEEE 30-bus system		
G1	0.0315	28.5	810
G2	0.0343	27.8	1270
G3	0.0432	28.0	660
G4	0.0200	30.0	1100
G5	0.0513	26.5	500
G6	0.0272	27.5	980
Gnew	0.0190	27.3	1400

Generator Emission coefficients

	d	*e*	*f*
	IEEE 14-bus system		
G1	0.00419	-0.3276	35.859
G2	0.00403	-0.1032	56.300
G3	0.00551	-0.2056	52.099
G4	0.00483	0.0555	30.266
G5	0.00600	0.0100	41.895
Gnew	0.00411	-0.2007	54.545
	IEEE 30-bus system		
G1	0.00423	-0.3378	37.525
G2	0.00416	-0.2012	55.321
G3	0.00407	-0.1055	57.518
G4	0.00564	-0.2089	53.336
G5	0.00499	0.0576	32.016
G6	0.00612	0.0130	44.164
Gnew	0.00430	-0.2165	54.002

Generation capacity limits for IEEE 14-bus system

Generator	1	2	3	4	5	New
P_G^{max} (MW)	90	70	60	50	40	100
P_G^{min} (MW)	50	30	30	10	10	50

Generation capacity limits for IEEE 30-bus system

Generator	1	2	3	4	5	6	New
P_G^{max} (MW)	80	70	60	50	40	40	100
P_G^{min} (MW)	50	30	30	10	10	10	50