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Economic dispatch in power system networks including renewable energy resources using various optimization techniques

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Abstract: Economic dispatch (ED) is an essential part of any power system network. ED is how to schedule the real power outputs from the available generators to get the minimum cost while satisfying all constraints of the network. Moreover, it may be explained as allocating generation among the committed units with the most effective minimum way in accordance with all constraints of the system. There are many traditional methods for solving ED, e.g., Newton-Raphson method Lambda-Iterative technique, Gaussian-Seidel method, etc. All these traditional methods need the generators' incremental fuel cost curves to be increasing linearly. But practically the input-output characteristics of a generator are highly non-linear. This causes a challenging non-convex optimization problem. Recent techniques like genetic algorithms, artificial intelligence, dynamic programming and particle swarm optimization solve nonconvex optimization problems in a powerful way and obtain a rapid and near global optimum solution. In addition, renewable energy resources as wind and solar are a promising option due to the environmental concerns as the fossil fuels reserves are being consumed and fuel price increases rapidly and emissions are getting higher. Therefore, the world tends to replace the old power stations into renewable ones or hybrid stations. In this paper, it is attempted to enhance the operation of electrical power system networks via economic dispatch. An ED problem is solved using various techniques, e.g., Particle Swarm Optimization (PSO) technique and Sine-Cosine Algorithm (SCA). Afterwards, the results are compared. Moreover, case studies are executed using a photovoltaic-based distributed generator with constant penetration level on the IEEE 14 bus system and results are observed. All the analyses are performed on MATLAB software.

Key words: Economic Dispatch (ED), Particle Swarm Optimization (PSO), Sine-Cosine Algorithm (SCA), Photovoltaic (PV)

1. Introduction

Nowadays, the main aspect that concern engineers is the cost of services and products. Decreasing the operating cost is crucial in all power system networks. Economic dispatch is getting the optimal output of a number of power generation units, to serve the system load, at the most reduced conceivable cost.

Solving computational complexity of the dispatching optimization strategies in power systems was troublesome earlier. Besides, these conventional optimization techniques can't ensure the quality of the ultimate solution.

Practically the curves of generators' input-output are various and non-linear due to numerous fuel impacts, ramp-rate limits and confined zones of operation.

The complex ELD (economic load dispatch) problem [11, 13, 14] has to be solved by contemporary heuristic or probabilistic search optimization methods like DP (dynamic programming) as described in [2, 6], GAs (genetic algorithms) as illustrated in [18], AI (artificial intelligence) [10] and PSO (particle swarm optimization) [1, 3, 4]. DP exhibits robustness, but sometimes shows slow convergence near the optimum point. While, GA is a probabilistic algorithm.

James Kennedy and Russell Eberhard introduce particle swarm optimization as in [5, 7, 24]. This technique fixes non-linear complex optimization problems. It was motivated by animal groups behavior like flocking of birds, schooling in fishes, etc. It operates without demanding information on the slope of objective or error function and it smoothly determines the best independent solution. The PSO method proposes a high-quality solution in a short time and displays rapid convergence.

In 2016, Mirjalili *et al*. initialised a further mathematics-based algorithm which is called Sine-Cosine Algorithm (SCA) as described in [20, 22]. The solutions in this algorithm update their positions to the most effective solution reached so far through sine-cosine mathematical functions. Conceptually, the SCA has few parameter settings and is easy to be implemented. On the other hand, the existing SCA has the disadvantage of a premature convergence problem and low optimization precision.

In this paper, the IEEE 14-bus system is considered. Economic scheduling of three generator units is executed using PSO technique and SCA. The results are compared. All the analyses are performed in MATLAB software.

Two case studies are executed using PV-based DG (distributed generator) supply to show its effect on the cost at a specific bus then at each bus of the IEEE 14 bus system using PSO technique.

Sections in this paper are divided as follows: Section 2 illustrates the economic dispatch problem equations, Section 3 introduces the various techniques in our analyses, Section 4 discusses the results found, Section 5 shows the effect of penetration of PVDG supply and finally, Section 6 determines the conclusions reached and the future work.

2. Problem formulation

Power stations or power plants are the industrial facilities for the generation of electric power. The type of the power station is determined according to the type of energy source utilized to turn the generator which differs vastly. Most power plants all over the world burn fossil fuels as coal, natural gas and oil to generate electricity. While nowadays there is an increase in the usage of clean energy sources as nuclear power and renewables as wind, solar, hydroelectric and geothermal.

For example, the nuclear power plants operate at constant output levels. While at hydro-stations, storing energy is apparently free so the operating costs do not carry any meaning. Therefore, only the fuel burnt cost in fossil plants shares to the dispatching process. The generator's operational costs include fuel, labor and maintenance. Costs of supplies, labor and maintenance are excluded since these are a fixed proportion of incoming fuel cost. Then only the fuel cost has to be considered.

The thermal power plant input is expressed in Btu/h. Active power output can be expressed in MW. In fossil fuel plants the output power is increased sequentially at the inlet of a steam-turbine by opening the valves. When a valve is just open, the throttling losses become large and when it is fully opened, throttling losses become smaller.

The objective economic dispatch (ED) problem is to minimize the fuel cost level of a power system over some appropriate period, while satisfying various constraints.

2.1. Objective function

The fuel cost curve may be modelled as a quadratic function of active power as shown below,

$$F(Gi) = \alpha + \beta P_{Gi} + \gamma P_{Gi}^2 \quad \$/\mathrm{h}, \tag{1}$$

where: F is the fuel cost per hour, P_{Gi} is the active power output of an i-th generator, α, β and γ cost coefficients of each generator in \$/h, \$/MWh and \$/MW^{2}h, respectively.

2.2. System constraints

In solving a constrained optimization problem, there are two types of constraints:

a) Equality constraints:

This constraint is the power balance equation which states that total generation equals total demand in addition to transmission losses.

$$\sum_{i=1}^{N} P_G - P_D - P_L = 0. \tag{2}$$

b) Inequality constraints:

The generator's kVA loading must not exceed a certain thermal limit. The thermal constraint restricts the maximum active power generation so that rise in temperature remains within limits.

$$P_{\min} \leq P \leq P_{\max}, \tag{3}$$

where: $P_{\min}$ is the minimum active power limit of each generator, P is the active power output of each generator and $P_{\max}$ is the maximum active power limit of each generator.

3. Optimization techniques used

3.1. Particle swarm optimization

In 1995, Kennedy and Eberhard initially developed the PSO algorithm as discussed in [8, 12, 16]. This method starts from two different thoughts. The primary thought is based on experiencing flocking habits of specific sorts of animals (as birds, ants and bees). The second one is associated with the study of evolutionary computation. This algorithm operates by looking for the search space for candidate solutions and evaluating them to some fitness function with respect to the associated criterion. Firstly, the PSO technique selects some candidate solutions randomly or

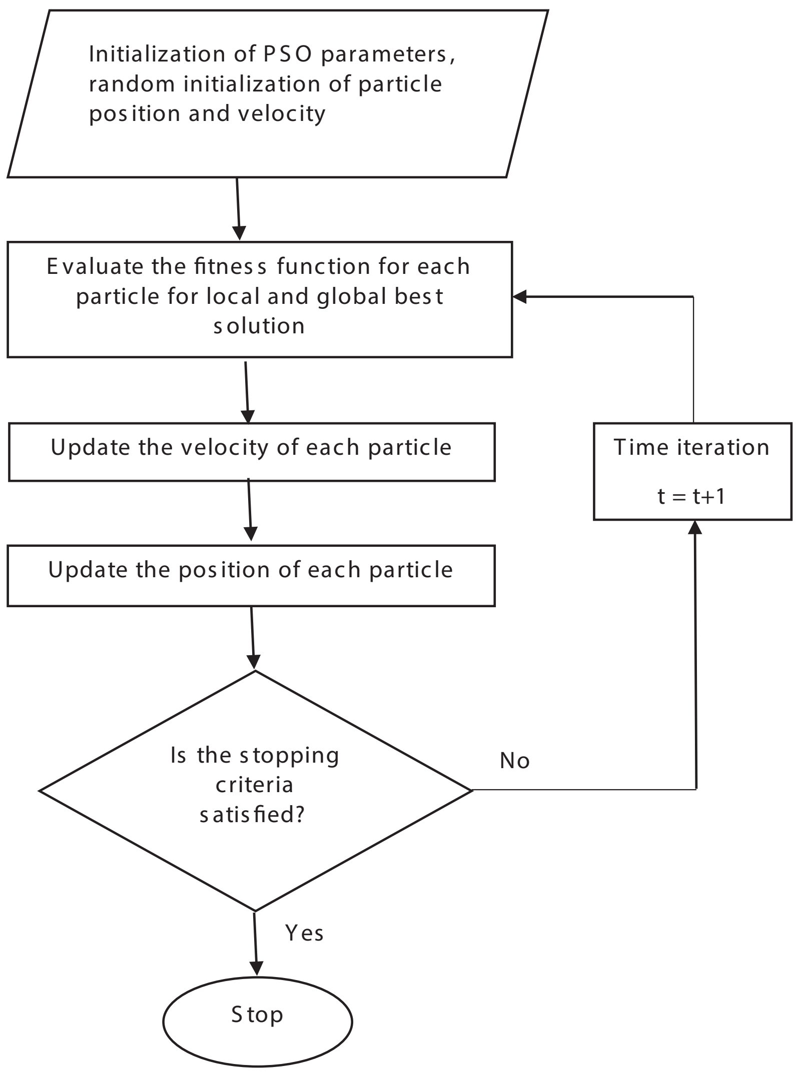

Fig. 1. Flow chart of PSO algorithm

may be set with prior knowledge. Then the position and velocity of each particle (candidate solutions) are evaluated against the fitness function. If the fitness function is not fulfilled, update the individual and social element with some update in the rule. Afterwards, update the position and velocity of the particles. This process is repeated iteratively until all the candidate solutions fulfill the fitness function and converge into a fixed position. It is significant to know that updating the position and velocity rule is essential in terms of the optimization capabilities of the PSO algorithm (Fig. 1).

The PSO technique is used several times in optimization tasks including solving economic load dispatch for a power system network as described in [8, 12, 16]. This stochastic and iterative method tries to drive particles and finally the swarm to obtain an optimal region then to obtain best point globally in the search space.

This method has greater flexibility in solving any constraint optimization problems, therefore it may be used to optimize a wide range of functions with multiple constraints.

This method is considered superior to other classical methods, as it does not need to solve complex mathematical formulas to find the best solution to the problem. Several modifications are applied to increase the performance and efficiency of this method in recent years.

3.2. Sine-Cosine Algorithm

The SCA is a population-based optimization technique. This technique starts with a random number of search agents as described in [17]. The optimization process is divided into two phases, namely exploration and exploitation. In the phase of exploration, the SCA combines all the random numbers of solutions in a set of solutions quickly with a higher rate of randomness so that it can find those regions of search space where there is a higher probability to find the global solution. On the other hand, in the phase of exploitation, there are slow changes in the random solutions and low random variations compared to the exploration phase (Fig. 2).

In the SCA, there are four main parameters, namely e1, e2, e3, and e4. The parameter e1 indicates the next position, which may be between the solution and the destination or even outside it. The parameter e2 decides the distance that the search agents have to cover in the direction of the solution. The parameter e3 helps to decide the weighting factor for the destination. Weighting factors greater than one indicate an increased emphasis on a destination and lower than one represent decreased emphasis. The parameter e4 equally switches between the sine and cosine components. Due to the involving property of switching between the sine and cosine functions, the algorithm is known as the SCA. The sine and the cosine functions have the tendency to re-position themselves around the global solution.

4. Results

Economic dispatch using PSO technique and SCA is implemented on MATLAB on 3 generators of the IEEE 14 bus system. This system has a minimum generation capacity of 50 MW and a maximum generation capacity of 330 MW. Several iterations were executed and the results are summarized in Tables 1 and 2, while the convergence characteristics of both algorithms are shown in Figures 3 and 4.

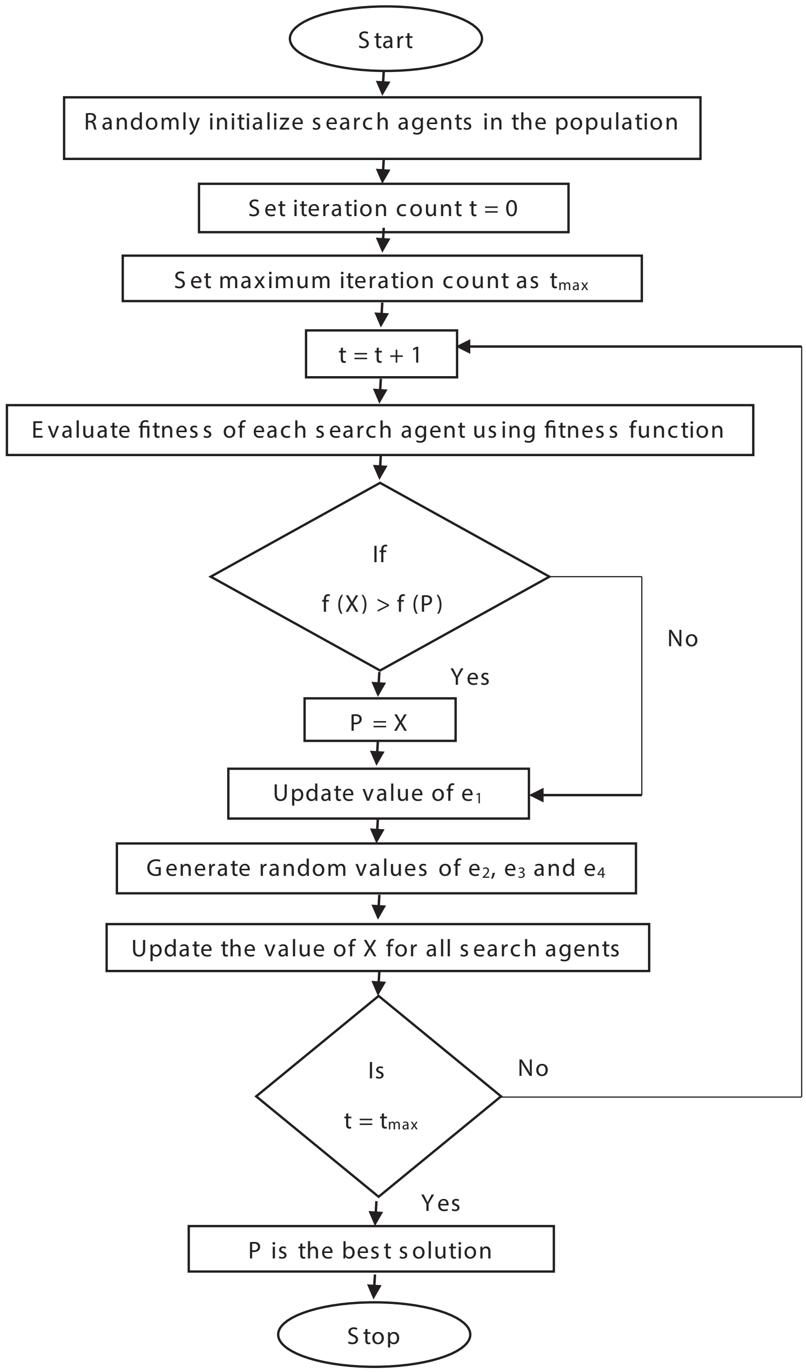

Fig. 2. Flow chart of SCA

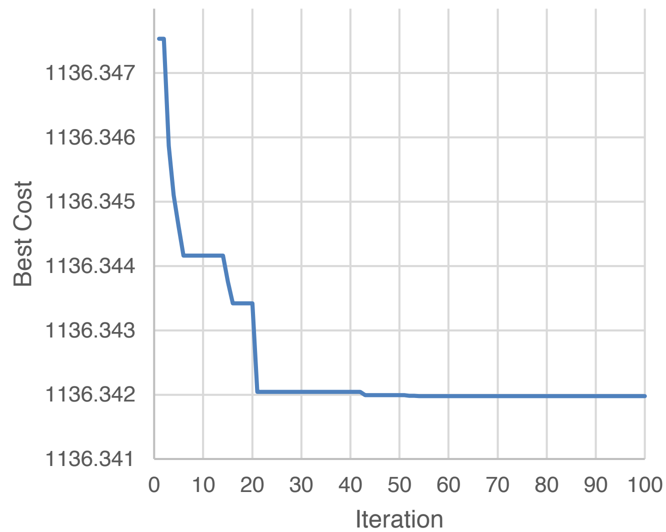

Fig. 3. Best cost versus number of iterations curve for PSO

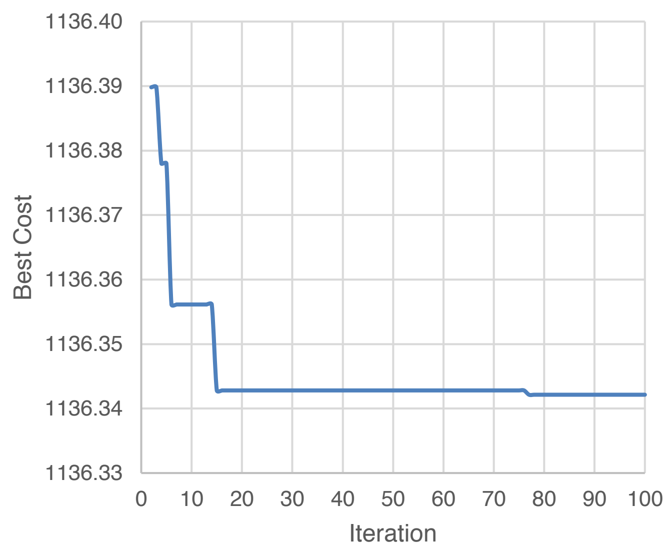

Fig. 4. Best cost versus number of iterations curve for SCA

Table 1 shows the output power of each generator of the 3 generators to get the minimum possible cost using the PSO technique. Therefore, the generation units compensate the total demand for this system, which is 259 MW, and the total active losses which equal 8.9 MW for a sum of 267.9 MW.

Table 1. Results summary using PSO

Generator unit	G1	G2	G3
$P_{o/p}$ (MW)	155.82	65.03	47.05

By substituting in Equation (1) with these values we get:

$$\textbf{Total cost of generation (min. cost)/hour} = \mathbf{1136.342\ \$/h},$$

$$\textbf{Total cost (min cost)/day} = \mathbf{1136.342 \times 24 = 27272.208\ \$}.$$

While by using the SCA we get the following results:

Table 2. Results summary using SCA

Generator unit	G1	G2	G3
$P_{o/p}$ (MW)	155.96	64.99	46.96

Here also Table 2 shows the output power of each generator of the 3 generators to reach the minimum possible cost using the SCA. The generation units compensate the total demand for this system, which is 259 MW, and in addition to the total active losses which equal 8.91 MW for a total sum of 267.91 MW.

Furthermore, by substituting in Equation (1) with these values we get:

$$\textbf{Total cost of generation (min. cost)/hour} = \mathbf{1136.3421\ \$/h},$$

$$\textbf{Total cost (min cost)/day} = \mathbf{1136.3421 \times 24 = 27272.2104\ \$}.$$

5. Effect of penetration of PV-based DG supply

Electrical power generation is amongst the most important sources of pollutant emissions. Burning of coal, fossil fuel and natural gas at power plants produces many pollutants such as carbon dioxide, sulfur dioxide and nitrogen oxide, etc. These gases can lead to many hazards as smog, and acid rain. Additionally, such emissions increase the danger of climate change. This problem may be limited by reduced dependence on fossil fuel plants and relying on the renewable energy resources as wind and solar.

Public awareness that regards the environmental issues is increasing and the usage of hybrid power systems including renewable sources as wind and solar is being obligatory in order to modify the generation techniques and to attenuate the emissions which pollute the atmosphere as in [9, 15].

In this study, solar irradiance per day on an hourly basis is used to see the effect of penetration of PV-based DG supply on the total cost and the economic dispatch problem.

The 24 h output of PV is calculated for various solar radiation at a specific location [15] and is listed as follows in Fig. 5 then the averaged output power is calculated to get Fig. 6.

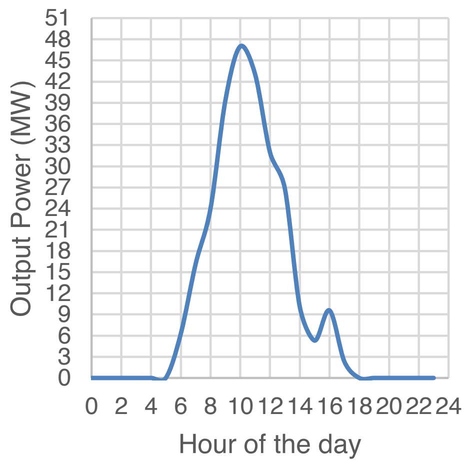

Fig. 5. Hourly basis of solar output power

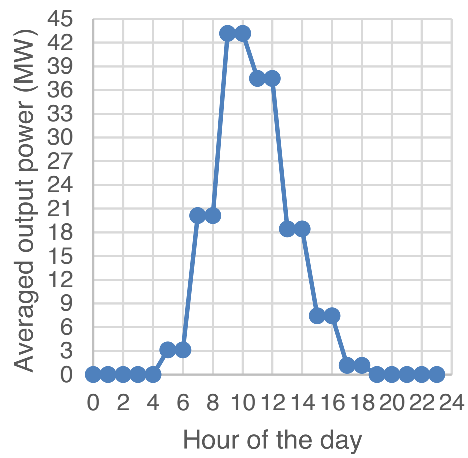

Fig. 6. Hourly basis of solar output power

i. Case study I

In this study, the PV DG is allocated at any bus and the total cost is calculated at this bus to observe the effect of penetration of PV-based DG supply on the total cost per day on this bus.

This study is executed on the IEEE 14 bus system using the PSO technique as in [19, 21] on MATLAB software, and any random bus is picked, e.g., the effect on bus 2 will be studied.

Data of Table 3, are the optimal output power for each generator P1, P2, and P3 on an hourly basis of a day. It appears that the total cost per hour decreases at the time of using the output power from PV supply with the main generators while it increases again in the period from 8 pm to 6 am, which is the period without the sun.

Table 3. Results for costs and output power of each generator for a single bus

Hours per day	P1 (MW)	P2 (MW)	P3 (MW)	Cost/h ($/h)
12–6 am	155.82	65.03	47.05	1136.34
6–8 am	154.82	63.84	46.1	1123.26
8–10 am	149.4	57.46	41	1053.42
10–12 pm	142.05	48.83	34.05	960.18
12–2 pm	143.87	50.97	35.77	983.10
2–4 pm	149.93	58.09	41.5	1060.25
4–6 pm	153.45	62.23	44.81	1105.51
6–8 pm	155.46	64.59	46.7	1131.54
8–12 am	155.82	65.03	47.05	1136.34
Total cost/day ($/day)				26197.93

Moreover, if the two results of using PV and without using PV are compared, it will be shown that the total cost per day decreases, obviously, with a PV unit. Not only decreasing costs of fossil fuels but also minimizing emissions will be achieved.

ii. Case study II

In this study, the total cost at each bus is calculated and the optimal bus to allocate the PV DG is observed to reach the minimum cost per day.

This study is performed on the IEEE 14 bus system using PSO technique as in [23] on MATLAB software.

Table 4. Results for costs and total cost at each bus

	12–6 am	6–8 am	8–10 am	10–12 pm	12–2 pm	2–4 pm	4–6 pm	6–8 pm	8–12 am	Total cost/day
Bus 1	1136.3	1123.7	1056.5	966.8	988.8	1063.1	1106.6	1131.7	1136.3	26237.9
Bus 2	1136.3	1123.3	1053.4	960.2	983.1	1060.2	1105.5	1131.5	1136.3	26197.9
Bus 3	1136.3	1122.6	1049.6	952.4	976.2	1056.7	1104.1	1131.3	1136.3	26149.2
Bus 4	1136.3	1122.6	1049.3	952.1	975.9	1056.5	1103.9	1131.3	1136.3	26146.6
Bus 5	1136.3	1122.7	1050.4	954.3	977.8	1057.4	1104.3	1131.3	1136.3	26160
Bus 6	1136.3	1122.7	1050.4	954.9	978.3	1057.5	1104.3	1131.3	1136.3	26162.4
Bus 7	1136.3	1122.6	1049.5	952.5	976.2	1056.6	1104.0	1131.3	1136.3	26148.6
Bus 8	1136.3	1122.6	1049.5	952.5	976.3	1056.6	1104.0	1131.3	1136.3	26148.8
Bus 9	1136.3	1122.6	1049.5	952.9	976.5	1056.7	1104.0	1131.3	1136.3	26150.4
Bus 10	1136.3	1122.5	1049.5	953.7	977.1	1056.6	1103.9	1131.3	1136.3	26152.8
Bus 11	1136.3	1122.6	1050.1	955.6	978.6	1057.2	1104.1	1131.3	1136.3	26162.5
Bus 12	1136.3	1122.5	1050.4	958.0	980.3	1057.4	1104.0	1131.3	1136.3	26171.2
Bus 13	1136.3	1122.5	1049.3	954.0	977.2	1056.4	1103.7	1131.2	1136.3	26151.9
Bus 14	1136.3	1122.3	1048.5	953.5	976.5	1055.6	1103.3	1131.2	1136.3	26144.9

Now the optimal location for PV-base DG supply is bus 14 as it has the lowest cost.

Moreover, the difference between a system with PV and without PV is obvious. The total cost per day with PV is 26144.935 $ while without PV is 27272.208 $.

6. Conclusions

In this paper, an optimal solution of the economic dispatch (ED) was proposed using PSO algorithm and SCA. PSO technique showed high quality solution and stable convergence over SCA. The total cost of generation in the case of the PSO technique appears to be less than the total cost in the case of the SCA. The plotted graph for the IEEE 14-bus system showed the convergence characteristics. PSO (particle swarm optimization) is superior in terms of reliable performance.

Furthermore, a renewable energy resource is introduced, which is PV with a constant penetration level, and the reduction in the total cost of generation is observed. Afterwards, this PV-based DG supply is allocated at its best place after searching for this place with respect to minimum cost. Several calculations are executed using PSO technique on MATLAB to reach the best place for PV DG.

Since the minimum cost is at bus 14, therefore with constant penetration level its best allocation is to be added at bus 14.

As part of further work, since the effect of PV-based DG supply is studied on the cost of the IEEE 14 bus system with constant penetration levels then this study may be extended to increase penetration levels and decreasing the emissions in addition to the cost.

Appendix A

Table A1. Generators data of IEEE 14 bus system

Bus	**Generator**	***P*min (MW)**	***P*max (MW)**	α **($/h)**	β **($/MW h)**	γ **($/MW h^2)**
1	G1	10	200	105	2.45	0.005
2	G2	20	80	44.1	3.51	0.005
3	G3	20	50	40.6	3.89	0.005

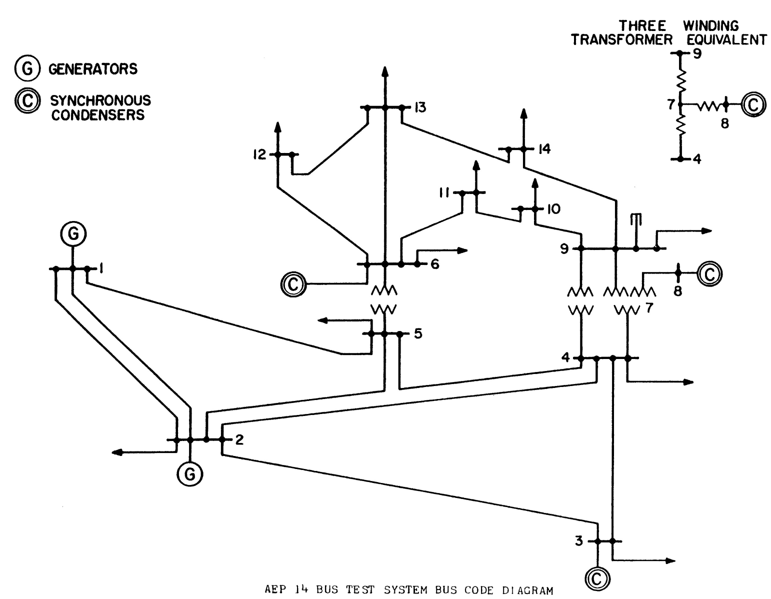

Fig. A1. Schematic diagram for IEEE 14 bus system

Table A2. Busses data of IEEE 14 bus system

	Generation		**Load**	
Bus	P_G **(MW)**	Q_G **(MVAR)**	P_D **(MW)**	Q_D **(MVAR)**
1	0	0	0	0
2	40	0	21.7	12.7
3	0	0	94.2	19
4	0	0	47.8	-3.9
5	0	0	7.6	1.6
6	0	0	11.2	7.5
7	0	0	0	0
8	0	0	0	0
9	0	0	29.5	16.6
10	0	0	9	5.8
11	0	0	3.5	1.8
12	0	0	6.1	1.6
13	0	0	13.5	5.8
14	0	0	14.9	5

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