

## Dynamic Economic Dispatch Problems: PSO Approach

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### Abstract

*Due to limited availability of coal and gases, optimization plays an important factor in thermal generation problems. The economic dispatch problems are dynamic in nature as demand varies with time. These problems are complex since they are large dimensional, involving hundreds of variables, and have a number of constraints such as spinning reserve and group constraints. Particle Swarm Optimization (PSO) method is used to solve these challenging optimization problems. Three test cases are studied where PSO technique is successfully applied.*

**Keywords:** dynamic economic dispatch, PSO, problem formulation, modelling

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### 1. Introduction

More than three-fourth of power generated in this world is through non-reusable resources like coal and gas. As these resources are limited, there is need to spend them judiciously. Thus, optimization plays a key role in the thermal generation problem. In this problem, fuel cost is minimized, and supply-demand matching is the equality constraint. This is referred to as the economic dispatch problem. In the 1920s, such problems were treated as static [1] where demand remained fixed for a given time. In the present scenario, the problem is more complex as demand varies with time resulting in suitable adjustment by each power plant to supply accordingly. Such time-varying demand-supply problems are termed as dynamic economic dispatch (DED) problems. Using optimization, a significant amount of power and cost can be saved. There is a saying, *power saved is power produced*.

The optimization problem not only has supply demand equality constraint but has to meet a number of inequality constraints as well. The ramp rate constraint ensures safe operations of thermal generators. Some other important constraints for the DED problems are:

1. Spinning reserve requirements
2. Generation capacity
3. Group constraints
4. Emission constraints
5. Security constraints

Attempts have been made to solve the dynamic economic dispatch DED problem as an optimization problem for each time step. However, this approach results in sub-optimal solution [2]. For example, in a 10 generator problem with 6 periods [3], the optimal solution gives the minimum cost as 85043 units whereas period by period optimized solution results into minimized cost as 85047 units. Table 1 and Table 2, summarize optimal dispatch solutions with the two approaches.

Clearly, an optimal solution obtained by period by period approach is inferior to the optimal solution obtained by considering all the periods together. Thus, there is a need to solve DED problem as a complete optimization problem. The DED problem should also have the capability to look ahead and predict power demand at a future time.

The DED problem was first solved using the optimal control formulation [4]. In this approach, state equations are provided, and co-state equations need to be derived. Further, if more constraints are added or deleted, optimal control technique requires a reworking of the formulation. Which makes it the major drawback of this method? At present, DED problems are solved using both gradient based (like, sequential quadratic programming) and stochastic methods (like Genetic Algorithm and Particle Swarm Optimization) [5-9].

Using PSO, the multi-objective economic dispatch problem [10] was solved by combining two contradictory objectives (emission and economic cost) with the use of penalty factor towards forming a single objective problem. The emission cost and the normal fuel costs are blended with the introduction of the price penalty factor. In order to find a solution to the bid-based dynamic economic dispatch in the context of a competitive electricity market, Zhao [11] utilized PSO with constriction factor and inertia weight. The maximization of social profit, which is the difference between a customer's benefit function to a generator's cost function, is the objective function of their study. Among the topics discussed in this paper are generation bid quantities; power balance; ramp rate limits; customer bid quantities; line limit, and emission as equality and inequality constraints in the optimization process.

On the other hand, a hybrid method involving PSO with sequential quadratic programming (SQP) is used to solve a DED problem. Their study considered several factors, namely ramp rate limit; real power balance; the voltage at load bus; generation limit; transmission line constraints; and spinning reserve as constraints to the problem. In order to fine-tune the solution region, this method integrates PSO algorithm as the global optimizer with SQP as a local optimizer.

In this paper, PSO (Particle Swarm Optimization) method is used to solve large dimensional economic dispatch problems. Because of its simplicity in solving the practical ED problem, population-based PSO has been recognized as the fast growing solution algorithm. The main advantage of PSO method is that it is more likely to find a globally optimal solution rather than local optima.

## 2. Problem Formulation

Ideally, thermal generating powerhouses should generate units which balance the consumer's load demand. The number of units generated by different power plants is the design variables that need to be determined, and typical objective function of the optimization problem is to minimize the overall cost of producing the number of demanded units. In DED, the number of units produced by thermal power plants varies with time so as to bridge the gap between demand and supply. The rate at which a thermal power plant can change its unit generating capacity is called as the ramp rate limit. This parameter is also known as loading and deloading rate limits of the generator. The ramp rate is defined based on practical considerations such as load and mechanical stresses on the generator. Thus, it takes a finite time to change the capacity of generating units for a thermal plant, as shown in Figure 1.

Table 1. Optimal Dispatch Solution

Generator	Period-1	Period-2	Period-3	Period-4	Period-5	Period-6
1	12	12	12	12	12	42
2	26	28	58	88	72	93
3	42	42	53	83	113	143
4	18	18	18	18	18	18
5	30	30	30	30	30	30
6	100	100	100	100	204	324
7	248	248	248	248	248	248
8	190	190	190	190	190	190
9	88	117	141	190	190	190
10	109	113	113	113	113	113
Cost	11124	11560	12522	14138	16146	19521
Total cost = 85011						

Table 2. Suboptimal Solution (Period by Period Dispatch)

Generator	Period-1	Period-2	Period-3	Period-4	Period-5	Period-6
1	12	12	12	12	12	42
2	26	26	31	61	91	93
3	42	42	42	72	102	132
4	18	18	18	18	18	18
5	30	30	30	30	30	49
6	100	100	100	138	196	316
7	248	248	248	248	248	248
8	190	190	190	190	190	190
9	88	119	179	190	190	190
10	113	113	113	113	113	113
Cost	11124	11558	12473	14203	16119	19570
Total cost = 85047						

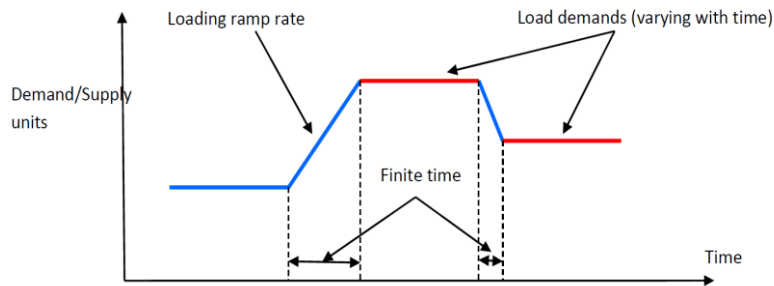


Figure 1. Typical Demand/Supply Unit Variations with Time

## 2.1. Basic Model

Ideally, thermal generating, the objective function for DED problem is to:

$$\text{Minimize } \sum_{t=1}^N \sum_{i=1}^n C_i(G_i^t) \quad (1)$$

Where  $C_i(G_i^t)$  is the cost of generating power from  $i$ th generating plant ( $G_i^t$ ) units at  $t^{\text{th}}$  time interval  $[(t-1)T, tT]$ . The design variables for the optimization problem are the vector  $(G_i^t)$  which tells about the number of units to be generated by the  $i^{\text{th}}$  thermal plant over each  $t$ th time interval.

The equality constraint depicting balance of supply and demand is given by:

$$\sum_{i=1}^n \sum_{t=1}^N G_i^t = D^t$$

This equation can be written as:

$$\mathbf{h} = \sum_{i=1}^n \sum_{t=1}^N G_i^t - D^t = 0 \quad (2)$$

The ramp rate limits are the inequality constraints and are written as:

$$R_{down}^i T \leq D^{t+1} - D^t \leq R_{up}^i T$$

can be written as two inequality constraints:

$$\mathbf{g} = \begin{bmatrix} D^{t+1} - D^t - R_{up}^i T \\ R_{down}^i T - D^{t+1} + D^t \end{bmatrix} \quad (3)$$

The inequality constraints are written in the standard form:

$$\mathbf{g} \leq 0$$

## 2.2 Additional Constraints

In addition to ramp rate limits, the DED problems considered in this paper has a spinning level and group constraints. The spinning level is the extra power that needs to be generated (more than the required demand) by each generator so that load variation and failure of some generators can be easily tolerated. The spinning reserve of generators is proportional to the generation level below a defined output known as the Spinning Reserve Level (SL) and equal to the spare capacity above SL (Figure 2). Mathematically,

$$S_i = \begin{cases} k_i G_i & \text{for } G_i^{min} \leq G_i \leq SL_i \\ G_i^{max} - G_i & \text{for } SL_i \leq G_i \leq G_i^{max} \end{cases}$$

Another type of constraint, called as the group constraint, wherein different generators combine output is limited by certain bounds. This may be due to the following reasons [1, 2, 12]:

1. Transmission line limitations
2. Regulatory restrictions
3. Area security considerations

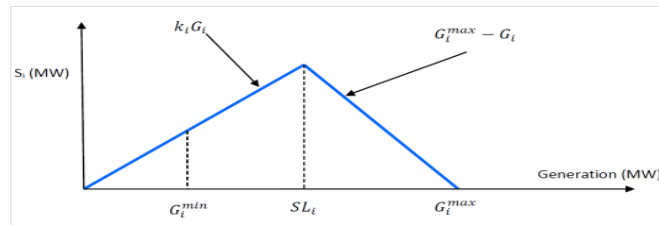


Figure 2. Spinning Reserve Contribution

## 3. Solution Technique

The PSO is a population-based stochastic optimization procedure which drew its inspiration from the social conduct of fish schooling or bird flocking [13]. This method and the evolutionary computation processes including Genetic Algorithms (GAs) are alike in many ways. The system sets out with a population of arbitrary solutions and forages for optima through the updating of generations. However, unlike GAs, PSO is devoid of evolution operators such as crossovers and mutations. In a PSO setting, the possible solutions (known as particles) soar through the problem area by staying on the heels of the existing optimum particles [14].

PSO forages for optimal answers to the problem through interaction with individuals in the swarm. A particle comprises two components; position and velocity. Position denotes the objective variable while velocity is the extent of the step a particle endeavours to take in the subsequent turn. A particle corresponds to a potential or candidate answer to the problem. The particles are tasked with the search for solutions in the multidimensional problem area in compliance with two major functions; their velocity and the adapted rules of position updating. Every particle progresses towards the optimal point through the increment of velocity to its position. Updating rules of position is the primary role of PSO with respect to the d-th dimension.

Once population size is decided, the first step in PSO is to generate random population within the specified values of the design variables. The algorithm given here is taken from Arora [15]. Let  $\mathbf{x}$  be a vector of design variables that need to be determined. Then, the position of the kth individual in the population is given by:

$$\mathbf{x}_k = \mathbf{x}_{min} + (\mathbf{x}_{max} - \mathbf{x}_{min})\mathbf{u} \quad (4)$$

Where  $\mathbf{x}_{min}$  and  $\mathbf{x}_{max}$  are the variable bounds and  $\mathbf{u}$  is a uniform distributed random number between 0 and 1. In the next step, fitness of k<sup>th</sup> individual is computed for the i<sup>th</sup> iteration as:

$$p_{i,k} = f(\mathbf{x}_{i,k}) \quad (5)$$

The minimum of the function obtained so far by each particle is given by  $pbest$  as:

$$pbest_{i,k} = minimum(p_{1...i,k}) \quad (6)$$

The global best for the group is given by  $gbest$  as:

$$gbest_i = minimum(pbest_{i,k}) \quad (7)$$

Let the position of  $pbest_{i,k}$  and  $gbest_i$  is given by  $p_{xik}$  and  $g_{xi}$ . In the next step of PSO, velocity of the particle is computed as:

$$v_{i+1,k} = w_1 v_{i,k} + \varphi_1 (p_{xik} - x_{i,k}) u_i + \varphi_2 (g_{xi} - x_{i,k}) u_i \quad (8)$$

where  $v_{i,k}$  is the velocity from the previous iteration (in the first iteration it set to zero). The tuning factors of the algorithm are given by  $w-1$ ,  $\varphi-1$  and  $\varphi-2$ . In the final step, position of the individual in the population is updated as:

$$x_{i+1,k} = x_{i,k} + v_{i+1,k} \quad (9)$$

In case the new position  $x_{i+1,k}$  is not within the desired bounds, a new value of  $x_{i+1,k}$  is generated using:

$$x_{i+1,k} = x_{min} + (x_{max} - x_{min}) u$$

This last equation completes an iteration of the PSO. The steps are repeated a finite number of times as desired by the user. A flow chart depicting different steps of PSO is shown in Figure 3.

A penalty function approach is followed in handling constraints. Using penalty function approach, a constraint optimization problem is converted into an unconstrained problem [15-16]. The modified objective function with penalty terms is written as:

$$F = f + r_k \sum_{j=1}^r h_j^2 + r_k \sum_{i=1}^m \langle g_i \rangle^2 \quad (10)$$

where  $r_k (> 0)$  is a penalty parameter and the function:

$$\langle g_i \rangle = \max[0, g_i] \quad (11)$$

In the next step,  $F$  is computed for each population point in the search space. Subsequently, the rest of the procedure of PSO remains same as described earlier.

#### 4. Case Studies

In order to evaluate the performance of the PSO algorithm, three DED problems are taken from the literature [3]. These problems are classified into simple and complex DED problems. In a simple problem (Case study-1), 10 generators are used to meet the demand which varies with time. The time duration is divided into six periods of 30 minutes each. The capacity of each generator is limited to a minimum and maximum values (Table 3). For example, generator-1 can operate between 12 MW and 73 MW. The ramp rate or the loading rate constraint is also defined for each generator. For example, generator-2 has a loading rate constraint of 1MW/minute. The power change in the next period can be  $\pm 30$  MW ( $1 \times 30 = 30$  MW). This means, if generator-2 is producing power say at 60 MW at a given time period, then in the next period (of 30 min), generator-2 power can be between 30 MW and 90 MW ( $60 \pm 30$ ).

The cost of generating each unit of power by the respective generator is also mentioned in Table 3. The power produced by each generator at the start of simulation is referred to in the last column of Table 3. The power generation bounds are pictorially represented in Figure 4. The power demand varying over different periods (of 30 minutes each) is shown in Figure 5. The DED problem is to find the output of each generator so that demand is met at each time

and overall cost is minimized. The rate at which generator power can be increased or decreased is limited by ramp rate constraint.

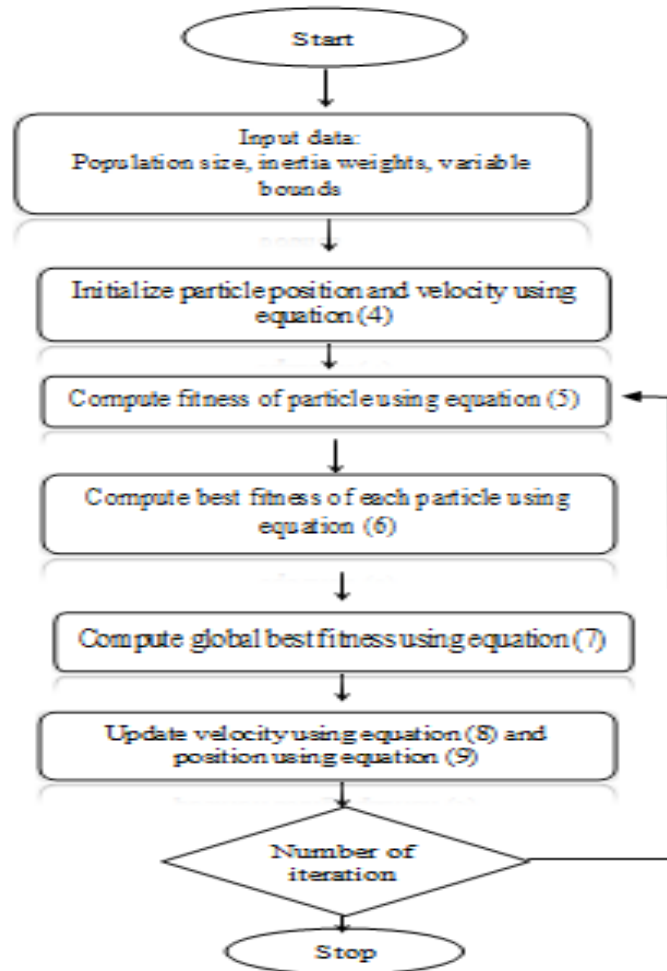


Figure 3. Flow Chart of PSO

Table 3. Input Parameters for Case-1

Generator No.	Generation limit (MW)		Loading rate (MW/min)	Cost (units)	Initial generation (MW)
	maximum	minimum			
1	73	12	1	18	12
2	93	26	1	15	26
3	143	42	1	16	42
4	70	18	1	20	18
5	93	30	1	19	30
6	350	100	4	17	100
7	248	100	4	11	248
8	190	40	2	10	190
9	190	70	2	14	70
10	113	40	2	12	60

In case study-2, there are 20 generators and 24 periods. The input data for this problem is given in Table A1(Appendix), while the demand and spinning requirements are mentioned in Table A2. The 100 generator and 5 periods are also a complex issue (case study-3). The input data for this problem is given in Table A3, while the demand and spinning requirements are

mentioned in Table A4. This particular problem has group constraints; where certain groups need to generate power between certain ranges. These details are given in Table A5.

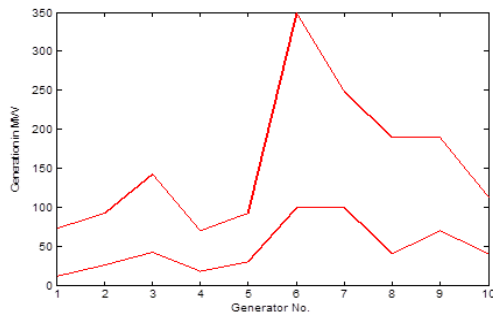


Figure 4. Power Generation Limits of Different Generators

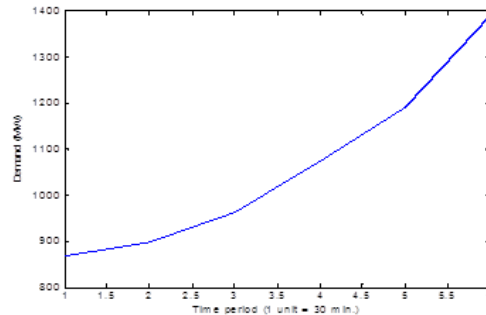


Figure 5. Demand Variation with Time

**5. Results and Discussion**

The PSO algorithm is coded in the MATLAB [17] environment. For case study-1 (10 generators, 6 periods problem), there are sixty design variables that need to be determined by the optimizer. The total cost is minimized to 85011 units, and the convergence history is shown in Figure 6. Since a penalty function approach is followed in PSO, the function value is very large at the beginning as constraints are not met. The function value gradually reduces as more and more constraints are satisfied. The optimal values of the design variables are mentioned in Table 1.

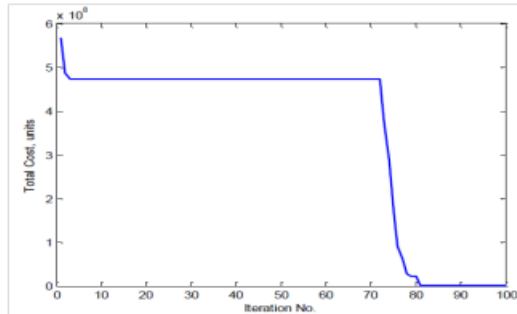


Figure 6. Convergence of Total Cost to optimal and Feasible Solution with PSO Method

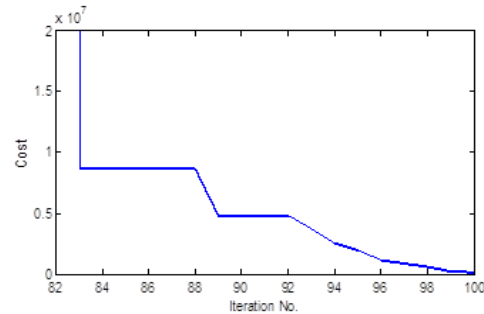


Figure 7. Convergence of Function (Case Study 2)

The case study-1 was further studied where a period by period optimization was done. The optimal cost obtained is 85047 units, and optimal design variables are mentioned in Table 2. Further, in case-study-1, constraints were relaxed, resulting in an optimal cost to be 84552 units and optimal design variables are mentioned in Table 4.

In case study-2, there are 20 generators and 24 periods. This results in an optimization problem where 480 (20 x 24) variables are to be evaluated. In addition to loading constraint, this problem has spinning level constraints. The 480 variables problem is solved using the PSO method. The total cost is minimized to 98836.58 units, and the convergence history is shown in Figure 7. Since a penalty function approach is followed in PSO, the function value is very large at the beginning as constraints are not met. The function value gradually reduces as more and more constraints are satisfied.

Due to the large scale of the graph (on the y-axis) in Figure 7, the objective function appears to be zero at convergence but has a value of 99135.12 units. As for period by period for this 20 generator and 24 period cases, the solution which results in Sub-optimal solution, the total cost is 98843.06 units. The following Table 5 summarizes the findings for this case of 20 generators and 24 periods.

Table 4. Infeasible Dispatch (Neglecting Ramp Rate Constraints)

Generator	Period-1	Period-2	Period-3	Period-4	Period-5	Period-6
1	12	12	12	12	12	16
2	26	26	26	93	93	93
3	42	42	42	78	143	143
4	18	18	18	18	18	18
5	30	30	30	30	30	30
6	100	100	100	100	153	350
7	248	248	248	248	248	248
8	190	190	190	190	190	190
9	88	119	184	190	190	190
10	113	113	113	113	113	113
Cost	11124	11558	12468	14133	16074	19495
Total cost = 84852						

Table 5. Results of PSO Method: 20-Generator System and 24 Periods

No	Case Solution	Generation cost (p.u.)
1	Optimal	98836.58
2	Sub-optimal (Period-by-period)	98843.06

In case study-3, there are 100 generators and 5 periods. This results in an optimization problem where 500 (100 x 5) variables are to be evaluated. In addition to loading constraint, this problem has spinning level constraints. The 500 variables problem is solved using the PSO method. The total cost is minimized to 659395.1 units as shown in Table 6, and the convergence history is shown in Figure 8. As for the period-by-period case, the PSO solution gives Sub-optimal cost of 659430 units as shown in Table 7. Since a penalty function approach is followed in PSO, the function value is very large at the beginning as constraints are not met. The function value gradually reduces as more and more constraints are satisfied. Due to the large scale of the graph (on the y-axis) in Figure 8.

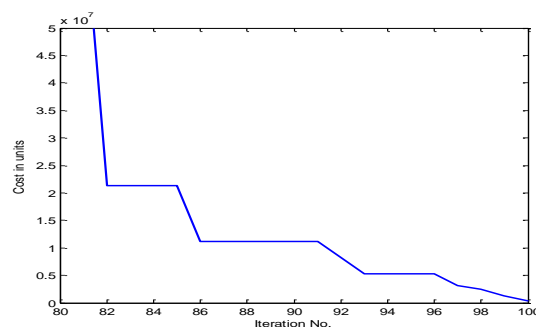


Figure 8. Convergence History (Case Study-3)



Table 6. Results for 100 Generators and 5 Periods, Optimal Solution – PSO Method

Generator Unit Number	Period				
	1	2	3	4	5
1	60.0	60.0	60.0	60.0	60.0
2	60.0	60.0	60.0	60.0	60.0
3	50.0	50.0	50.0	50.0	50.0
4	40.0	40.0	40.0	40.0	40.0
5	40.0	40.0	40.0	40.0	40.0
6	90.0	100.0	100.0	100.0	100.0
7	90.0	100.0	100.0	100.0	100.0
8	375.0	375.0	375.0	375.0	375.0
9	375.0	375.0	375.0	375.0	375.0
10	375.0	375.0	375.0	375.0	375.0
11	375.0	375.0	375.0	375.0	375.0
12	53.4	53.4	53.4	53.4	53.4
13	53.3	53.3	53.3	53.3	53.3
14	53.3	53.3	53.3	53.3	53.3
15	90.0	90.0	90.0	90.0	90.0
16	90.0	90.0	90.0	90.0	90.0
17	100.0	100.0	100.0	100.0	100.0
18	100.0	100.0	100.0	100.0	100.0
19	100.0	100.0	100.0	100.0	100.0
20	90.0	90.0	90.0	90.0	90.0
21	90.0	90.0	90.0	90.0	90.0
22	90.0	90.0	90.0	90.0	90.0
23	40.5	60.0	40.0	60.0	40.0
24	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0
26	30.0	60.0	30.0	60.0	0.0
27	28.8	50.0	50.0	50.0	43.1
28	28.8	50.0	50.0	50.0	43.1
29	60.0	60.0	60.0	60.0	60.0
30	60.0	60.0	60.0	60.0	60.0
31	60.0	60.0	60.0	60.0	60.0
32	90.0	90.0	90.0	90.0	90.0
33	90.0	90.0	90.0	90.0	90.0
34	90.0	90.0	90.0	90.0	90.0
35	90.0	90.0	90.0	90.0	90.0
36	90.0	90.0	90.0	90.0	90.0
37	50.0	50.0	50.0	50.0	50.0
38	50.0	50.0	50.0	50.0	50.0
39	33.6	49.0	49.0	45.0	39.7
40	33.6	41.0	41.0	45.0	39.7
41	33.6	50.0	50.0	50.0	46.2
42	50.0	50.0	50.0	50.0	50.0
43	50.0	50.0	50.0	50.0	50.0
44	50.0	50.0	50.0	50.0	50.0
45	20.0	50.0	50.0	50.0	20.0
46	0.0	0.0	0.0	0.0	0.0
47	50.0	50.0	50.0	50.0	50.0
48	50.0	50.0	50.0	50.0	50.0
49	50.0	50.0	50.0	50.0	50.0
50	50.0	50.0	50.0	50.0	50.0
51	10.0	10.0	10.0	10.0	10.0
52	0.0	0.0	0.0	25.0	0.0
53	0.0	0.0	0.0	25.0	0.0
54	0.0	0.0	0.0	0.0	0.0
55	0.0	0.0	0.0	0.0	0.0
56	60.0	60.0	60.0	60.0	60.0
57	60.0	60.0	60.0	60.0	60.0
58	60.0	60.0	60.0	60.0	60.0
59	0.0	40.0	40.0	40.0	26.2
60	20.0	40.0	40.0	40.0	20.0
61	20.0	40.0	40.0	40.0	20.0
62	30.0	50.0	20.0	40.0	20.0
63	20.0	50.0	20.0	50.0	20.0
64	10.0	40.0	20.0	50.0	20.0
65	32.7	40.0	20.0	40.0	20.0
66	75.0	75.0	75.0	75.0	75.0
67	75.0	75.0	75.0	75.0	75.0
68	56.0	56.0	56.0	56.0	56.0

69	56.0	56.0	56.0	56.0	56.0
70	56.0	56.0	56.0	56.0	56.0
71	56.0	56.0	56.0	56.0	56.0
72	56.0	56.0	56.0	56.0	56.0
73	50.0	50.0	50.0	50.0	50.0
74	10.0	37.5	18.0	37.5	20.0
75	10.0	37.5	18.0	37.5	20.0
76	10.0	37.5	18.0	37.5	20.0
77	10.0	37.5	29.7	37.5	22.0
78	60.0	60.0	60.0	60.0	60.0
79	60.0	60.0	60.0	60.0	60.0
80	50.0	50.0	50.0	50.0	50.0
81	500.0	500.0	500.0	500.0	500.0
82	200.0	200.0	200.0	200.0	200.0
83	500.0	500.0	500.0	500.0	500.0
84	48.4	50.0	46.3	50.0	50.0
85	50.0	50.0	50.0	50.0	50.0
86	50.0	50.0	50.0	50.0	50.0
87	50.0	50.0	50.0	50.0	50.0
88	50.0	50.0	50.0	50.0	50.0
89	40.0	40.0	40.0	40.0	40.0
90	60.0	60.0	60.0	60.0	60.0
91	60.0	60.0	60.0	60.0	60.0
92	50.0	50.0	50.0	50.0	50.0
93	60.0	60.0	60.0	60.0	60.0
94	0.0	0.0	0.0	45.0	0.0
95	0.0	10.0	0.0	45.0	0.0
96	40.0	50.0	50.0	50.0	40.0
97	20.0	20.0	20.0	50.0	20.0
98	20.0	20.0	20.0	50.0	20.0
99	20.0	20.0	20.0	50.0	20.0
100	0.0	20.0	0.0	0.0	0.0

Period Number	ON-Line Generation Cost PSO (u.c.) OPTIMAL
1	125393.20
2	135820.00
3	130543.70
4	140220.00
5	127418.20
<b>Total Cost PSO -OPT</b>	<b>659395.10</b>

The following Table 7, summarize the findings for the results of particle swarm optimization case of 100 generator and 5 periods (with 22 group import – export constraints) where two solutions were compared.

Table 7. PSO method: 100 – generators 5 Periods - case

No	Case Solution	Generation cost (p.u.)
1	Optimal	659395.10
2	Sub-optimal (Period-by-period)	659430.00

## 6. Conclusion

The PSO method is used to solve dynamic economic dispatch problems. Three large dimensional economic dispatch optimization problems had 60, 480 and 500 design variables respectively. The ease with which PSO code can be modified for different problems (addition or deletion of constraints) shows the versatility of PSO method in addition to its accuracy.

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**Appendix (Ab Ghani, M.R., 1989 [3])****Table A1. Input parameters for the 20 generators DED problem**

Generator No.	Generation limit (MW)		Loading rate (MW/hr)	De-loading rate (MW/hr)	Cost (units)	SL (MW)
	maximum	minimum				
1	430	360	300	600	1.0000	0
2	410	360	300	600	1.0063	0
3	82	50	180	600	1.0111	77
4	82	50	180	600	1.0124	77
5	82	50	180	600	1.0137	77
6	82	50	180	600	1.0150	77
7	430	250	300	900	1.0629	411
8	430	300	300	900	1.0636	411
9	430	140	300	900	1.0643	411
10	102	70	240	360	1.1304	92
11	483	130	180	600	1.1318	463
12	483	130	180	600	1.1325	463
13	483	130	180	600	1.1332	463
14	483	130	180	600	1.1339	463
15	102	70	240	360	1.1464	92
16	102	70	240	360	1.1512	92
17	56	30	120	600	1.1548	51
18	56	30	120	600	1.1565	51
19	57	30	300	360	1.2327	52
20	28	15	120	120	1.4457	26

**Table A2. Demand and Spinning Reserve Data**

Period	Demand (MW)	Required reserve (MW)
0	4346	80
1	4240	80
2	4214	80
3	4124	80
4	4097	80
5	4074	80
6	4173	80
7	4267	80
8	4147	80
9	3918	80
10	3690	80
11	3769	80
12	3851	80
13	3825	80
14	3776	80
15	3847	80
16	3859	80
17	3778	80
18	3567	80
19	3335	80
20	3220	80
21	3247	80
22	3418	80
23	3856	80
24	3983	80

**Table A3. Input parameters for the 100 generators DED problem**

Generator No.	Generation limit (MW)		Loading rate (MW/hr)	De-loading rate (MW/hr)	Cost (units)	SL (MW)
	maximum	minimum				
1	60	10	120	180	19	55
2	60	10	120	180	19	55
3	60	10	120	180	20	55
4	60	10	120	180	20	55
5	60	10	120	180	20	55
6	100	20	120	360	20	90
7	100	20	120	360	20	90
8	500	50	1000	1500	15	0
9	500	50	1000	1500	15	0
10	500	50	1000	1500	15	0
11	500	50	1000	1500	15	0
12	60	10	120	300	19	55
13	60	10	120	300	19	55

14	60	10	120	300	19	55
15	100	20	120	300	20	90
16	100	20	120	300	20	90
17	100	20	120	300	19	90
18	100	20	120	300	19	90
19	100	50	120	300	20	94
20	100	20	120	300	20	90
21	100	20	120	300	20	90
22	100	20	120	300	20	90
23	60	10	30	180	21	55
24	50	20	30	180	22	48
25	40	10	30	180	22	38
26	60	30	30	180	21	56
27	50	10	60	180	20	46
28	50	10	60	180	20	46
29	60	10	120	300	19	55
30	60	10	120	300	19	55
31	60	10	120	300	19	55
32	100	20	120	300	20	90
33	100	20	120	300	20	90
34	100	20	120	300	20	90
35	100	20	120	300	20	90
36	100	20	120	300	19	90
37	50	10	60	180	19	46
38	50	10	60	180	19	46
39	50	10	60	180	20	46
40	50	10	60	180	20	46
41	50	10	60	180	20	46
42	50	20	60	180	19	46
43	50	10	60	180	19	46
44	50	10	60	180	19	46
45	50	20	60	180	21	48
46	50	20	60	180	22	48
47	60	10	60	180	19	55
48	60	10	60	180	19	55
49	60	10	60	180	19	55
50	60	10	60	180	19	55
51	30	5	30	180	22	28
52	30	5	30	180	22	28
53	30	5	30	180	22	28
54	30	5	30	180	22	28
55	30	5	30	180	22	28
56	60	10	60	180	20	55
57	60	10	60	180	20	55
58	60	10	60	180	20	55
59	50	20	60	180	21	48
60	50	20	60	180	21	48
61	50	20	60	180	21	48
62	50	30	60	180	21	48
63	50	20	60	180	21	48
64	50	10	60	180	21	48
65	50	20	60	300	21	48
66	100	20	60	300	18	46
67	100	20	60	180	18	48
68	60	20	60	180	20	90
69	60	10	60	180	20	90
70	60	10	60	180	20	55
71	60	10	60	180	20	55
72	60	10	60	180	20	55
73	50	10	60	180	19	46
74	50	10	60	180	21	46
75	50	10	60	180	21	46
76	50	10	60	180	21	46
77	50	10	60	180	21	46
78	60	20	60	180	20	55
79	60	20	60	180	19	55
80	50	10	60	180	15	46
81	500	50	1000	1500	16	0
82	400	40	1000	1500	15	0
83	500	50	1000	1500	20	0
84	50	10	60	180	19	46
85	50	10	60	180	19	46

86	50	10	60	180	19	46
87	50	10	60	180	19	46
88	50	10	120	180	19	46
89	40	10	120	180	19	38
90	60	20	120	180	20	55
91	60	20	120	180	20	55
92	50	10	120	180	20	46
93	60	20	120	180	20	55
94	50	10	120	180	22	46
95	50	10	120	180	22	46
96	50	30	120	180	21	48
97	50	20	120	180	22	48
98	50	20	120	180	22	48
99	50	20	120	180	22	48
100	50	20	120	180	22	48

Table A4. Demand and Spinning Reserve Data

Period	Demand (MW)	Required reserve (MW)
0	6464	240
1	7000	240
2	7500	240
3	7250	240
4	7700	240
5	7100	240

Table A5. Group Constraints Data

Group limits		Generators in group
Lower	Upper	
40	250	1,2,3,4,5
40	200	6,7
100	1500	8, 9, 10, 11
20	160	12, 13, 14
140	750	15, 16, 17, 18, 19, 20, 21, 22
40	200	23, 24, 25, 26
20	2000	27, 28
10	450	32, 33, 34, 35, 36
10	190	37, 38, 39, 40
10	150	45, 46
40	200	47, 48, 49, 50
10	160	51, 52, 53, 54, 55
30	200	56, 57, 58
100	300	59, 60, 61, 62, 63, 64, 65
40	150	66, 67
10	280	68, 69, 70, 71, 72
50	200	73, 74, 75, 76, 77
50	180	78, 79, 80
120	1200	81, 82, 83
60	6000	84, 85, 86, 87, 88, 89
20	4000	90, 91, 92, 93
100	200	96, 97, 98, 99, 100