IJIREEICE

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 4, Issue 4, April 2016

Investigations on Evolutionary Programming and Particle Swarm Optimization Algorithms for Solving Economic Dispatch with Prohibited Operating Zones and Ramp - Rate Limit Constraints for Thermal Scheduling Problems

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Abstract: This paper proposes a Evolutionary Programming (EP) and Particle Swarm Optimization (PSO) algorithms to solve Economic Dispatch (ED) problems considering of prohibited operating zones, ramp rate limits, generator capacity limits and power balance constraints. The PSO method was developed through the simulation of a simplified social system and has been found to be robust in solving continuous nonlinear optimization problems in terms of accuracy of the solution and it can out perform other algorithms The EP and PSO algorithms are applied for the ED of three unit, six unit and fifteen unit thermal systems. The numerical results shows that the comparision of EP and PSO algorithms with some other other modern metaheuristic optimization methods reported in the recent literatures.

Keywords: Economic dispatch, Evolutionary programming, Particle swarm optimization, , Prohibited operating zones, Ramp rate limits.

1. INTRODUCTION

Increasing day-to-day power demands, scarcity of energy resources and increasing power generation costs necessitates optimal economic dispatch(ED) in today's power system. Economic dispatch problem has become one of the most important power system optimization problems in real time application.

The main objective of the economic dispatch problem in the power system is to find the optimal combination of power generation that minimizes the total fuel cost while satisfying the system constraints [1]. Many conventional methods such as a Lambda iteration method, Newton's method, Gradient Method, Linear programming method, Interior point method and Dynamic programming method have been applied to solve the basic economic dispatch(ED) problems [2]. In all these methods, the fuel cost function considered as quadratic in nature. However, in reality, the input-output characteristics of the generating units are to be non-linear due to prohibited operating zones, and ramp rate limit constraints. The Lambda-iteration method has been applied to many software packages and used by power utilities for solving ED problems due to ease of implementation. Since the lambda iteration method requires a continuous problem formulation, it cannot be directly applied to ED problems with discontinuous prohibited operating zones. For the selection of initial conditions, Newton's method is very much sensitive [3]. The gradient method suffers from the problem of convergence in the presence of inequality constraints. The linear programming method provides optimal results in less computational time, but the results are not accurate due to linearization of the problem.

Interior point method is faster than the linear programming method, but it may provide infeasible solution if the step size is not chosen properly [3].

Dynamic Programming (DP) method is one of the best conventional approaches to solve the ED problems with non-convex and unit cost functions. However, the DP method may cause the problems of the curse of dimensionality or local optimality [4] in the solution procedure.

Practically, ED problem is non-linear, non-convex type with multiple local optimal points due to inclusion of equality, inequality constraints, and prohibited operating zones. Conventional/classical methods have failed to solve such type of problems and converge into local optimal solution [5]. All these methods assume that the cost curve is continuous and monotonically increasing. To overcome the problems of conventional methods for solving ED problems, the researcher puts into their step by using modern meta -heuristic searching techniques, including simulated annealing (SA) [6], Modified Hopfield network method [7], Genetic Algorithm method (GA) [8], Evolutionary Programming method [9-13], Tabu search algorithm (TSA)[14], Particle swarm optimization method(PSO) [15-18] have been applied to solve the complex non-linear ED problems. But these methods do not always guarantee a global optimal solution.

In Simulate annealing method, annealing schedule is very closely related to performance optimization. However, a poor tuning of the annealing schedule may inadvertently affect the performance of simulated annealing. Hop field neural network method requires external training routines. Recently, researchers have identified some deficiencies in GA performance [8]. The premature convergence of the GA degrades its performance and reduces its search capability that leads to a higher probability towards obtaining only the local optimal solutions [15] .The other drawback of GA is premature convergence leading to local minima and the complicated process of coding and decoding the problem [19]. Evolutionary programming method for ED problem is more efficient than the GA method in computation time and can generate a high-quality solution with a shorter calculation. Particle swarm optimization is one of the latest versions of natural inspired algorithms which characteristics of high performance and easy implementation. PSO has a character of parallel searching mechanism, so it has high probability to determine the global (or) near global optimal solutions for the non-linear ED problems. The main drawback of the conventional PSO is its premature convergence, especially while handling the problems with more local optima and heavier constraints [19]. The another drawback of PSO is sensitive to the tuning of some parameters and weighting factors.

In this paper, a particle swarm optimization (PSO) method is proposed to solve non-linear ED problems taking into consideration of power balance constraint, generator operating limits, ramp rate limits and prohibited operating zones. The results obtained by the proposed algorithm are compared with EP, using MATLAB and the other methods which are reported in the recent literatures.

The performance of the proposed method has been investigated on three different power systems, and the results are tabulated for comparison with other methods.

2. PROBLEM FORMULATION

The objective of ED problem is to minimize the total generation cost of thermal generating units,while satisfying various system constraints, including power balance equation, generator power limits, prohibited operating zones and ramp rate limit constraints.

The problem of ED is multimodal, non-differentiable and highly nonlinear. Mathematically, the problem can be stated as in (1) [2, 20]

$$\text{Min } F_T = \sum_{i=i}^{N} F_i(P_i) \qquad (1)$$

$$i = 1, 2, 3, \ldots, N$$

where F_T is the total fuel cost, N is the number of generating units in the system. $F_i(P_i)$ is the fuel cost function of unit i and P_i is the output power of unit i. Generally, the fuel cost of generation unit can be expressed as

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i \left(Rs/hr\right) \qquad (2)$$

Where a_i, b_i and c_i are the cost coefficients of unit i
Subject to

2.1 Real power balance constraint

$$\sum_{i=1}^{n} P_i = P_D + P_L \qquad (3)$$

Where P_D is real power demand and P_L is the transmission loss.

The transmission loss (P_L) can be expressed in a quadratic function of generation (Using B-loss coefficient matrix).

$$P_L = \sum_{i=1}^{N} \sum_{j=1}^{N} P_i B_{ij} P_j + \sum_{i=1}^{N} B_{0i} P_i + B_{00} \qquad (4)$$

Where P_i and P_j are the power generation of i^{th} and j^{th} units and B_{ij} , B_{oi} , B_{oo} are the B – loss coefficients

2.2 Generator operating limits

The power output of each unit i restricted by its maximum and minimum limits of real power generation and is given by

$$P_{i\,min} \le P_i \le P_{i\,max} \qquad (5)$$

Where $P_{i\,max}$ and $P_{i\,min}$ are the maximum and minimum generation limits on i^{th} unit respectively.

2.3 Prohibited operating zone constraints

The generators may have the certain range where operation is restricted due to the physical limitation of steam valve, component, vibration in shaft bearing etc., The consideration of poz creates a discontinuity in fuel cost curve and converts the constraint as below

$$P_i \in \begin{cases} P_{i\,min} \le P_i \le P_{i,1} \\ P^{u}_{i,k-1} \le P_i \le P^{L}_{i,k} \\ P^{u}_{i,zi} \le P_i \le P^{L}_{i\,max} \end{cases} \qquad (6)$$

Where, $P^L_{i,k}$ and $P^u_{i,k}$ are the lower and upper boundary of K^{th} prohibited operating zone of unit i, k is the index of the prohibited operating zone, and Z_i is the number of prohibited operating zones (Figure1)

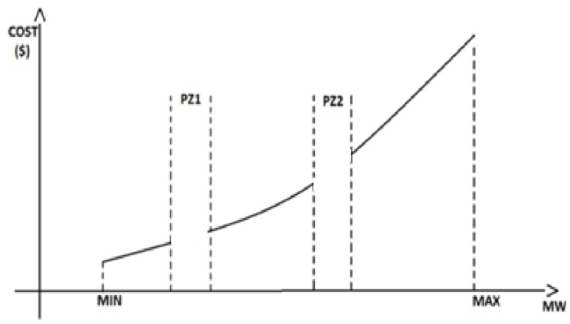

Fig. 1. Cost function with Prohibited operating zones

2.4 Ramp rate limit constraints

The generator constraints due to ramp rate limits of generating units are given as

(i) As generation increases

$$P_{i(t)} - P_{i(t-1)} \le UR_i \qquad (7)$$

(ii) As generation decreases

$$P_{i(t-1)} - P_{i(t)} \le DR_i \qquad (8)$$

Therefore the generator power limit constraints can be modified as

 DOI 10.17148/IJIREEICE.2016.4411

$$Max\ (P_{i\min}, P_{i(t-1)} - DR_i) \le P_{i(t)} \le Min\ (P_{i\max}, P_{i(t-1)} + UR_i) \quad (9)$$

From eqn. (9), the limits of minimum and maximum output powers of generating units are modified as

$$P_{i\min} = Max\ (P_{i\min}, P_{i(t-1)} - DR_i) \quad (10)$$

$$P_{i\max} = Min\ (P_{i\max}, P_{i(t-1)} + UR_i) \quad (11)$$

Where $P_{i(t)}$ is the output power of generating unit i in the time interval (t), $P_{i(t-1)}$, is the output power of generating unit i in the previous time interval (t-1), UR_i is the up ramp limit of generating unit i and DR_i is the down ramp limit of generating unit i.

The ramp rate limits of the generating units with all possible cases are shown in Figure 2.

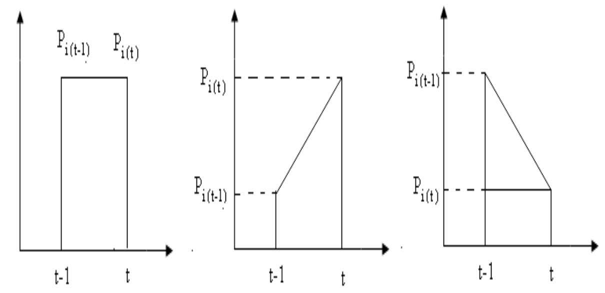

Fig. 2. Ramp rate limits of generating units

3. OVERVIEW OF EVOLUTIONARY PROGRAMMING

Four-decade earlier EP was proposed for evolution of finite state machines, in order to solve a prediction task. Since then, several modifications, enhancements and implementations have been proposed and investigated. Mutation is often implemented by adding a random number or a vector from a certain distribution (e.g., a Gaussian distribution in the case of classical EP) to a parent. The degree of variation of Gaussian mutation is controlled by its standard deviation, which is also known as a 'strategy parameter' in an evolutionary search [27]. The EP is near global stochastic optimization method starting from multiple points, which placed emphasis on the behavioral linkage between parents and their offspring rather than seeking to emulate specific genetic operators as observed in nature to find an optimal solution

3.1 EP general algorithm

Evolutionary programming is conducted as a sequence of operations and is given below. The basic steps and the flowchart for EP general algorithm is shown in Fig. 3.

Step 1 Choose an initial Population of trial solutions at random.

Step 2 Each solution is replicated into a new Population. Each of these offsprings solutions are mutated according to a distribution of mutation types, ranging from minor to extreme with a continuum of mutation types between

Step 3 Each offspring solution is assessed by computing it's fitness.

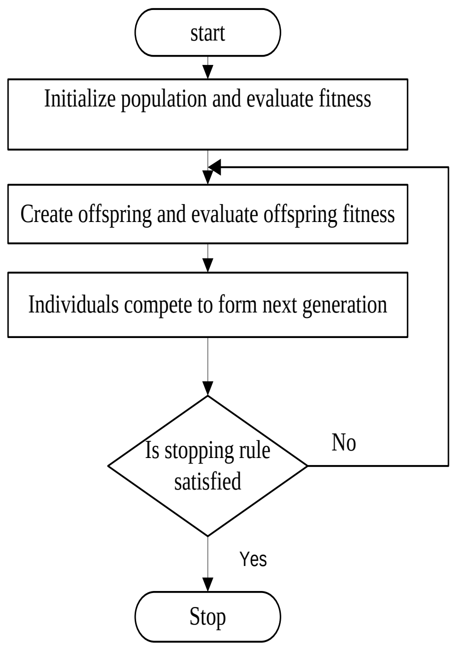

Fig. 3. Flowchart for EP general algrithm.

4. OVERVIEW OF PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is a population based stochastic optimization technique which can be effectively used to solve the non-linear and non-continuous optimization problems. It inspired by social behavior of bird flocking or fish schooling. The PSO algorithm searches in parallel using a group of random particles similar to other AI-based optimization techniques.

Eberhart and Kennedy suggested a particle swarm optimization based on the analogy of swarm of bird and school of fish [15]. PSO is basically developed through simulation of bird flocking in two- dimensional space. The position of each agent is represented by XY axis position, and also the velocity is expressed by Vx (velocity of X axis) and Vy (velocity of Y axis). Modification of the agent (particle) position is realized by the position and velocity information. Bird flocking optimizes a certain objective function. Each agent knows its best value so far (pbest) and its XY position. This information is the analogy of personal experiences of each agent. Moreover, each agent knows the best value so far in the group (gbest) among pbests. This information is the analogy of knowledge of how other agents around them have performed. The particles are drawn stochastically toward the position of the present velocity of each particle, their prior best performance and the best previous performance of their neighbor [16-17]. Each agent tries to modify its position using the following information:

1. The current position (x, y),
2. The current velocities (Vx, Vy),
3. The distance between the current position and pbest,
4. The distance between the current position and gbest.

This modification is represented by the concept of velocity. The velocity of each agent could be modified by the following equation (12)

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 4, Issue 4, April 2016

$$V_{id}^{(t+1)} = w \times V_{id}^{(t)} + C_1 \times rand\ () \times \left(pbest_{id} - P_{id}^{(t)}\right) + C_2 \times Rand\ () \times \left(gbest_d - P_{id}^{(t)}\right)$$
$$i = 1,2,\dots,\ n;\ d = 1,2,\dots,\ m \qquad (12)$$

Where 'n' is the population size, 'm' is the number of units and the 'w' be the inertia weight factor. Suitable selection of the inertia weight factors provides a balance between global and local explorations, thus requires fewer iteration on average to find a sufficiently optimal solution [15]. In general, the inertia weight w is set according to equation (13)

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} * iter \qquad (13)$$

Where,
Wmin and Wmax are the minimum and maximum weight factors respectively.
Wmax =0.9; Wmin =0.4
Iter – Current number of iterations
iter max – Maximum no of iterations (generations)
C_1, C_2 – Acceleration constant, equal to 2
rand( ), Rand( )–Random number value between 0 and 1
$V^{(t)}_{id}$ – Velocity of agent i at iteration t
$P^{(t)}_{id}$ – Current position of agent i at iteration t
pbest i – pbest of agent i
gbest – gbest of the group

Using the above equation, a certain velocity, which gradually gets close to pbest and gbest, can be calculated. The current position can be modified by equation (14)

$$P_{id}^{(t+1)} = P_{id}^{(t)} + V_{id}^{(t+1)} \qquad (14)$$

The first term of the right-hand side of equation (12) is corresponding to diversification in the search procedure. The second and third terms of that are corresponding to intensification in the search procedure. The PSO method has a well-balanced mechanism to utilize diversification and intensification in the search procedure efficiently. Figure 3 shows the concept of modification of a searching point by PSO. .

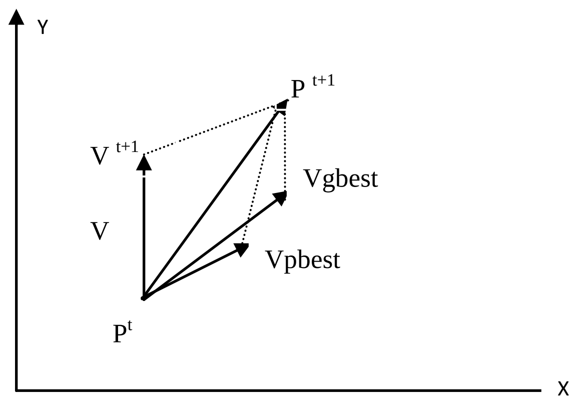

Fig. 3. Concept of modification of a searching point by PSO

Where
P^t : Current searching point
P^{t+1} : Modified searching point
V^t : Current velocity
V^{t+1} : Modified velocity
V pbest : Velocity based on pbest
Vgbest : Velocity based on gbest

4.1 Implementation of PSO for solving ED problem

The implementation of PSO method for solving ED problem is given as follows and the general flowchart of PSO is shown in Figure 4.
Step 1. Generate an initial population of particles with random positions and velocity within the solution space
Step 2. Calculate the value of the fitness function for each particle
Step 3. To compare the fitness of each particle with each pbest. If the current solution is better than its pbest, then replace its pbest by the current solution.
Step 4. Compare the fitness of all the particles with gbest. If the fitness of any particle is better than gbest, then replace gbest.
Step 5. Modify the velocity and position of all particles according to equations (12) & (14).
Step 6. Repeat the steps 2-5 until a criterion is met.

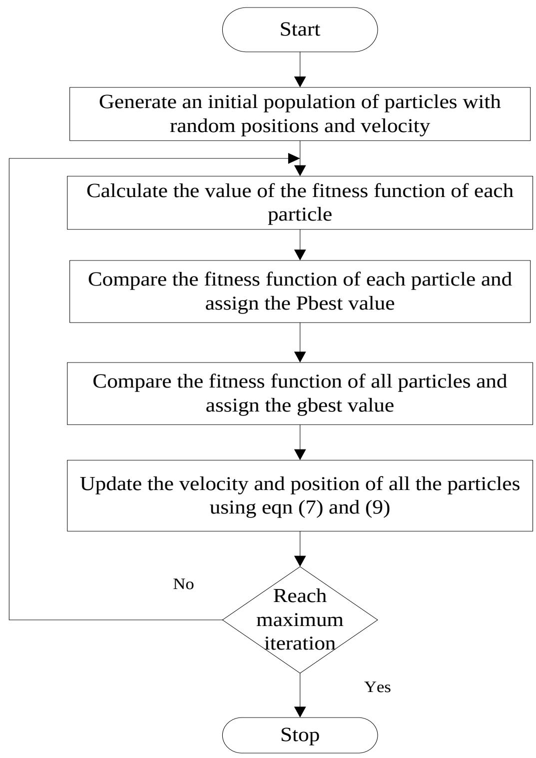

Fig. 4. General flowchart of PSO method

5. RESULTS AND DISCUSSION

To verify the feasibility of the EP and PSO methods , three different test systems are considered such as three, six and fifteen units with ramp rate limits and prohibited operating zones constraints. Results of the PSO and EP methods are compared with other methods, which are presented in the literatures. 100 trails runs were performed and observed the variations during the evolutionary process to reach convergence characteristics and optimal solutions. The B-loss coefficient matrix of power system network was employed to calculate the transmission line losses. The software was written in Mat Lab language and executed on

DOI 10.17148/IJIREEICE.2016.4411

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ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 4, Issue 4, April 2016

the third generation Intel Core i3 processor based personal computer with 4 GB RAM. From the comparison of results, the PSO method is found to be better in solving the non-linear ED problems.

Test System 1 A three-unit system [28] is considered, The system load demand is 300MW. The dimension of population is 100*3 and number of generations are 100. 100 trail runs are conducted, and the best solutions are shown in Table 1 that satisfies the system constraints. The results of the EP and PSO methods are compared with GA [28] and 2PNN [29] methods. From the comparison of the results, the fuel cost obtained by the PSO method is better than the other methods..

Table 1. Results of three unit system with POZ and RRL

Method	GA [28]	2PNN [29]	EP	PSO
P1(MW)	194.265	165.00	199.53	190.59
P2(MW)	50.00	113.40	75.68	85.77
P3(MW)	79.627	34.00	39.22	34.80
∑Pi(MW)	323.892	312.45	313.40	311.16
P_L(MW)	24.011	12.45	13.40	12.41
Fuel Cost($/hr)	3737.16	3652.60	3641.70	3631.1

Test system 2 The system contains six thermal units, 26 buses and 46 transmission lines [15]. The load demand is 1263MW. The losses are calculated using B-loss coefficient matrix. Theu dimension of the population is 100*6 and number of generations is taken as 100. 100 trial runs were conducted and the best solutions are shown in Table2. The results obtained by the EP and PSO are compared with GA [15], MTS[30] ,BBO [31] HHS [32] , TSA[33] and BA[34] methods. From the comparison of results, it clearly shows the PSO method gives minimum fuel cost than the other methods.

Table 2. Results of six unit system with POZ and RRL

Method	GA [15]	MTS [30]	BBO[31]	HHS[32]	TSA[33]	BA[34]	EP	PSO
P1(MW)	474.80	449.37	447.3997	449.9094	451.73	438.65	431.31	457.26
P2(MW)	178.63	182.23	173.2392	172.7347	185.23	167.90	170.33	160.72
P3(MW)	262.20	254.29	263.3163	262.9643	260.93	262.82	241.50	247.53
P4(MW)	134.28	143.45	138.006	136.03	133.10	136.77	147.98	131.52
P5(MW)	151.90	161.97	165.4104	166.967	171.08	171.76	182.64	170.50
P6(MW)	74.18	86.02	87.0797	86.8778	73.51	97.67	101.48	106.62
∑Pi(MW)	1276.0	1273.33	1275.446	1275.487	1275.58	1275.57	1275.2	1274.1
P_L(MW)	13.02	10.33	12.446	12.4834	12.58	12.59	12.69	11.15
Fuel Cost($/hr)	15459	15451	15443.09	15448.37	15449.2	15445.9	15451	15433

Test system 3 The input data of 15 unit test system are taken from reference [15]. The load demand of the system is 2630MW. The prohibited operating zones and ramp-rate limits are considered as the generator constraints. The losses are calculated using B-loss coefficient matrix. The dimension of the population is 100*15 and number of generations is taken as 100. The results obtained by the EP and PSO methods are compared with GA [15] method and are shown in Table 3. From the comparison of results, it is observed that the PSO method gives minimum fuel cost than the other methods.

Table 3. Results of fifteen unit system with POZ and RRL

Method	GA [15]	Evolution Strategy [35]	EP	PSO Proposed
P1	415.31	455.00	455.00	455.00
P2	359.72	380.00	380.00	380.00
P3	104.42	130.00	116.13	130.00
P4	74.99	150.00	119.06	130.00
P5	380.28	168.92	157.26	150.20
P6	426.79	459.43	460.00	460.00
P7	341.32	430.00	430.00	430.00
P8	124.79	97.42	151.68	60.00
P9	133.14	30.62	52.17	74.01
P10	89.26	142.56	99.11	160.00
P11	60.06	80.00	52.27	80.00
P12	50.00	85.00	65.48	80.00

P13	38.78	15.00	49.77	26.88
P14	41.94	15.00	35.85	21.74
P15	22.64	15.00	34.96	15.00
∑Pi	2668.40	2653.85	2658.70	2652.63
P_L	38.28	23.89	38.28	22.65
Fuel cost ($/hr)	33113	32568.54	33113	32640

6. CONCLUSION

In this paper, EP, and PSO methods are applied successfully to solve the non-linear economic dispatch problems. The proposed PSO has been proved to have superior features in terms of achieving better optimal solutions for reducing the fuel cost of the generating units and improving the convergence characteristics. Non-linear characteristics of the generators such as prohibited operating zones and ramp-rate limit constraints are considered for the selected test systems. The results obtained by the PSO method are compared with the EP, and other methods reported in recent literatures. The comparative study was done based on the optimum fuel cost. From this study, it can be concluded that the PSO method can be an alternative approach for finding a better solution for the nonlinear economic dispatch problems

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