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Economic Dispatch Using Hybrid Particle Swarm Optimization with Prohibited Operating Zones and Ramp Rate Limit Constraints

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Abstract – This paper proposes a new Hybrid Particle Swarm Optimization (HPSO) method that integrates the Evolutionary Programming (EP) and Particle Swarm Optimization (PSO) techniques. The proposed method is applied to solve Economic Dispatch(ED) problems considering prohibited operating zones, ramp rate limits, capacity limits and power balance constraints. In the proposed HPSO method, the best features of both EP and PSO are exploited, and it is capable of finding the most optimal solution for the non-linear optimization problems. For validating the proposed method, it has been tested on the standard three, six, fifteen and twenty unit test systems. The numerical results show that the proposed HPSO method is well suitable for solving non-linear economic dispatch problems, and it outperforms the EP, PSO and other modern metaheuristic optimization methods reported in the recent literatures.

Keywords: Economic dispatch, Evolutionary programming, Particle swarm optimization, Hybrid 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 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]. Dynamic Programming (DP) method is one of the best conventional approach 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 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's have put 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 Simulated 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. Recent researchers have identified some deficiencies in GA performance [8]. The premature convergence of GA degrades its performance and reduces its search capability

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that leads to a higher probability towards obtaining only the local optimal solutions [15]. The another drawback of GA is premature convergence leading to local minima and the complicated process in coding and decoding the problem [19]. Evolutionary Programming method for ED problem is more efficient than 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 nature 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. The proper and appropriate parameter tuning is absolutely necessary for quality solution. In order to overcome this troublesome parameter setting process, many researchers have proposed adaptive techniques. Zong Woo Geem has proposed parameter setting free Harmony search (PSFHS) technique to solve economic dispatch problem [20]. The results of PSFHS technique are quite encouraging in terms of convergence pattern and solution quality.

Various attempts have been made to overcome the problem of conventional (normal) PSO. Adaptive optimization algorithm must obtain a better balance between the local and global search ability, which means that the algorithm must has the ability to maintain a better local exploitation and global exploration ability. Among them, many adaptive approaches and strategies are proposed to enhance the performance of PSO. Self adaptive real coded GA [21], Iteration PSO with time varying acceleration coefficient [22] have been proposed to solve different types of non-convex ED problems. One of the well-known improved PSO algorithms of the parameter modifying method is inertia weight PSO, by introducing the inertia weight; the performance of the conventional PSO is improved. Empirical studies of PSO with inertia weight have been shown that a relatively large value of *w* have more global search ability while a relatively small value of *w* results in a faster convergence.

The performance of the PSO via adjusting inertia weight such as Fuzzy adaptive particle swarm optimization [23] Linearly Decreasing Weight [LDW] [24] Increasing Inertia Weight [25] and Randomized Inertia Weight [26, 27] have been proposed to solve different types of ED problems. In [24], Shi and Eberhart introduced the inertia weight to the velocity update equation of the original PSO. The present of the inertia weight increases the convergence speed greatly, and obtain a better balance between exploitation and exploration of the solution space while having little increase of the algorithm complexity. The strategy of linearly decreasing weight (LDW) is most commonly used and it can improve the performance of PSO to some extent, but it may be trapped in local optima and fail to attain high search accuracy.

In recent years, combinations of two different optimization techniques were introduced by researcher's to improve their earlier results. The following quoted here are some examples from recent literatures, which have used the combination of two different optimization techniques to solve the non linear economic dispatch problems. Simulated Annealing-Particle Swarm Optimization (SA-PSO) [28], Self Tuning Hybrid Differential Evolution (STH DE) [29], Variable Scaling Hybrid Differential Evolution (VSHDE) [30], Improved Genetic Algorithm with Multiplier Updating (IGAMU) [31], Quantum-inspired version of the PSO using the harmonic oscillator (HQPSO) [32], Self-Organizing hierarchical Particle Swarm Optimization (SOH-PSO) [33], and Bacterial Forging with Nelder-Mead Algorithm (BFA-NM) [34].

The main objective of the present work is to develop a hybrid algorithm which will be suitable for larger systems and to avoid premature convergence. The result obtained by the proposed algorithm is compared with EP, PSO which are developed using MATLAB and also with other intelligent techniques reported in the recent literatures.

The rest of this paper is organized as follows : section 2 introduces the problem formulation; section 3 explains over view of EP and PSO; section 4 presents a description of step by step development and solution methodology of the proposed HPSO method; section 5 shows the results and discussion and conclusion is summarized in section 6.

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 non-linear. Mathematically, the problem can be stated as in (1) [2, 21]

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

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

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

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

Where a_i, b_i and c_i are the cost coefficients of unit i subjected to the following constraints.

2.1 Real power balance constraint

$$\sum_{i=1}^{n} P_i = P_D + P_L \tag{3}$$

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).

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

where P_i and P_j are the power generation of ith and jth units and B_{ij}, B_{0i}, B_{00} are the B – loss coefficients.

2.2 Generator operating limits

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

$$P_{i\min} \le P_i \le P_{i\max} \tag{5}$$

where $P_{i\min}$ and $P_{i\max}$ are the minimum and maximum generation limits on ith 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 prohibited operating zone (poz) creates a discontinuity in fuel cost curve and converts the constraint as below

$$P_i \in \begin{cases} P_{i\min} \le P_i \le P^l_{i,1} \\ P^u_{i,k-1} \le P_i \le P^l_{i,k} \\ P^u_{i,z_i} \le P_i \le P_{i\max} \end{cases} \tag{6}$$

k=2,3,….z_i and i=1,2,…...N

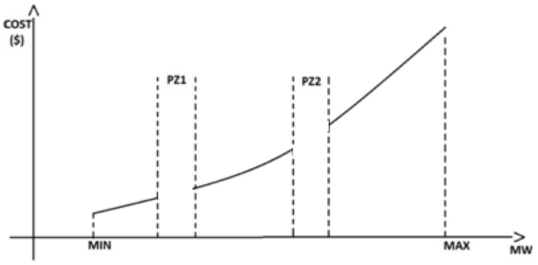

Fig. 1. Cost function with Prohibited operating zones

where, $P^L_{i,k}$ and $P^u_{i,k}$ are the lower and upper boundary of kth 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 (Fig. 1)

2.4 Ramp rate limit constraints

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

P As generation increases

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

As generation decreases

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

Therefore the generator power limit constraints can be modified as

$$\begin{aligned} &Max(P_{i\min}, P_{i(t-1)} - DR_i) \le P_{i(t)} \\ &\le Min(P_{i\max}, P_{i(t-1)} + UR_i) \end{aligned} \tag{9}$$

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

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

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

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 Fig. 2.

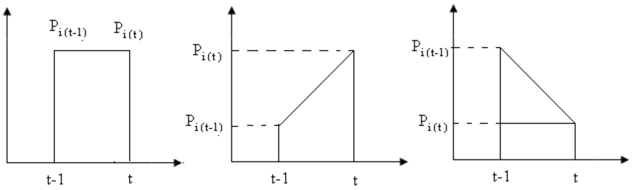

Fig. 2. Ramp rate limits of generating units

3. Overview of EP and PSO

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 [35]. 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.

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 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. Velocity of each agent could be modified by the following Eq. (12)

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

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 Eq. (13)

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} * iter \tag{13}$$

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 closer to pbest and gbest, can be calculated. The current position can be modified by Eq. (14)

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

The first term of the right-hand side of Eq. (12) is corresponding to the 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 the diversification and intensification in the search procedure efficiently. Fig. 3 shows the concept of modification of a searching point by PSO.

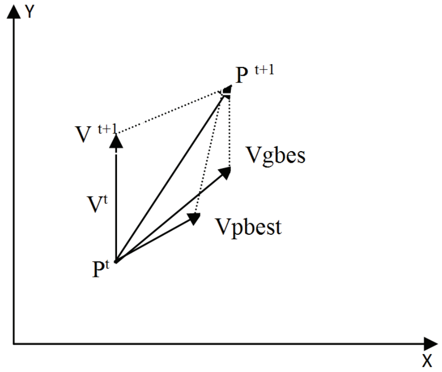

Fig. 3. Concept of modification of a searching point by PSO

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

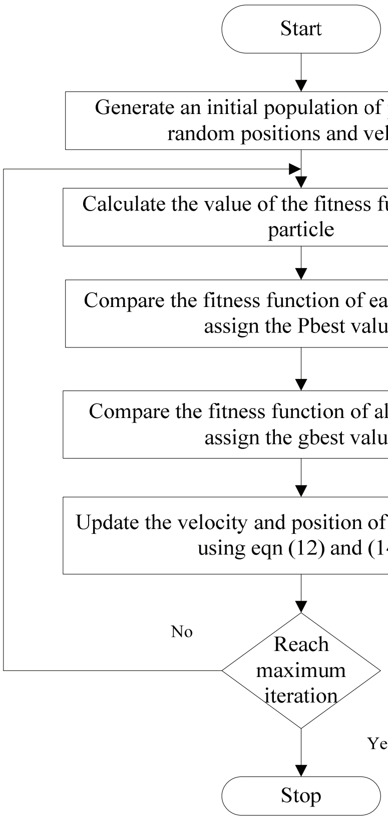

Fig. 4. General flowchart of PSO method

Vgbest : Velocity based on gbest

3.1 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 Fig. 4.

Step 1. Generate an initial population of particles with random positions and velocities 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 Eqs. (12) & (14).

Step 6. Repeat the steps 2-5 until a criterion is met.

4. Step by Step Development and Solution Methodology of the Proposed HPSO Method

Combining the special features of EP and PSO, the proposed HPSO has been developed, and the steps are given as follows.

4.1 Step by step development of the HPSO method

Step 1. Randomly generate the initial searching points of real power generation of generators and velocities within the allowable range. The current searching point is set to pbest for each agent. The best evaluated value of pbest is set to be gbest and gbest value is stored.

Step 2. Modification of searching point of each agent is changed using Eqs. (12), (13) and (14) and the corresponding evaluation values are calculated.

Step 3. If the evaluation value of each agent is better than the previous pbest, then the value is set to be pbest. If the best pbest is better than previous gbest, then the value is set to be gbest.

Step 4. Modification of searching points using Gaussian mutation and the evaluation values are calculated.

Step 5. If the evaluation value of each agent is better than the previous pbest, then the value is set to be pbest. If the best pbest is better than previous gbest, then the value is set to be gbest.

Step 6. If the current iteration number reaches the predetermined maximum iteration number, then exit. Otherwise, go to step 2.

4.2 Solution methodology of the proposed HPSO method to solve ED problem

The step by step procedure of the proposed HPSO method for solving ED problem is given below and the flow chart is shown in Fig. 5.

Step 1. Specify the generation limits of each unit and calculate F_{max} and F_{min}. Randomly initialize the individuals of the population according to limits of each unit including velocity, search points and individual dimensions. This initial individual must be feasible candidate solution that satisfies the practical operating constraints. Initial velocity limits of each member in individual is

$$V_d^{\max} = 0.5P_d^{\max};\ V_d^{\min} = -0.5P_d^{\min} \tag{15}$$

where,

$$P_d^{\max} = \sum_{i=1}^{n} P_i^{\max} \ \text{ and } \ P_d^{\min} = \sum_{i=1}^{n} P_i^{\min}$$

Step 2. For each Pi of the population use B-coefficients loss formula given in Eq. (4) to calculate the transmission loss

Step 3. Calculate the evaluation value of each individual Pi in the population using the Eq. (16)

$$f = \frac{1}{F_{\cos t} + P_{pbc}} \tag{16}$$

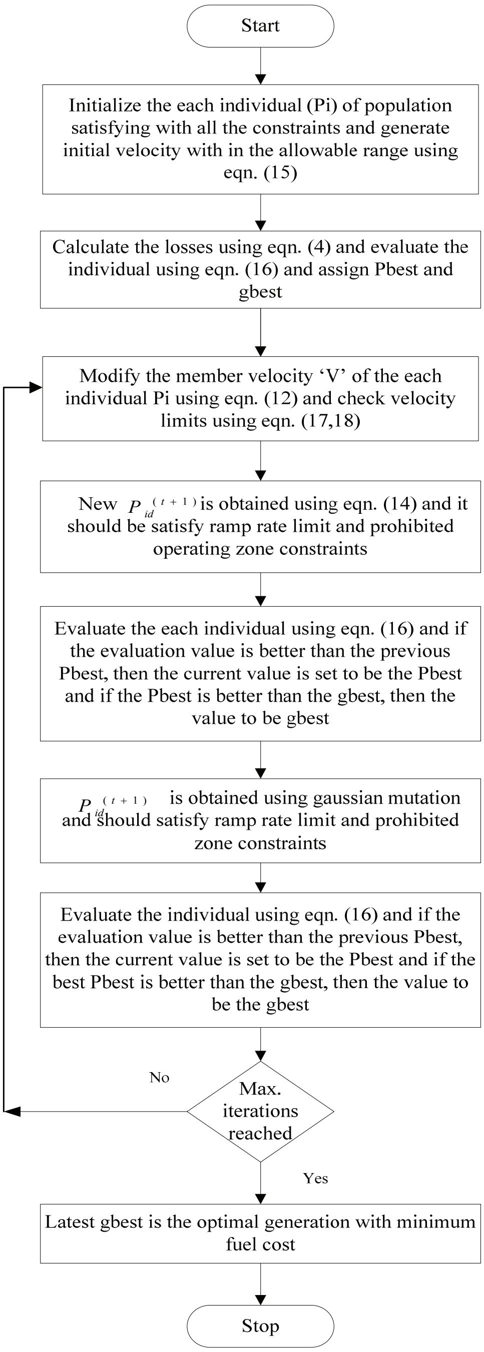

Fig. 5. The flow chart of the proposed HPSO method

where

$$F_{\cos t} = 1 + abs \frac{\left[\sum_{i=1}^{n} F_i(P_i) - F_{\min} \right]}{F_{\max} - F_{\min}}$$

$$P_{pbc} = 1 + \left[\sum_{i=1}^{n} P_i - P_D - P_L \right]^2$$

$F_{\max}$ and $F_{\min}$ are the maximum and minimum generation cost among all individuals in the initial population respectively.

In order to limit the evaluation value of the each individual of the population with in a feasible range before estimating the evaluation value of an individual, the generation output power must satisfy the constraints

Step 4. Compare each individual's evaluation value with its pbest values. The best evaluation value among the pbest values is assigned as gbest value.

Step 5. Modify the member velocity V of the each individual Pi using Eq. (12)

Step 6. Check the velocity components constraint limits from the following conditions.

$$\text{If } V_{id}^{(t+1)} > V_d^{\max}\text{, then } V_{id}^{(t+1)} = V_d^{\max,} \tag{17}$$

$$\text{If } V_{id}^{(t+1)} < V_d^{\min}\text{, then } V_{id}^{(t+1)} = V_d^{\min} \tag{18}$$

Step 7. Modify the member position of each individual Pi using the Eq. (14)

$P_{id}^{(t+1)}$ must satisfy the constraints of prohibited operating zone and ramp rate limits.

Step 8. If the evaluation value of each individual is better than the previous pbest value, then the current value is set to be pbest. If the best pbest is better than gbest, then the pbest is assigned as the gbest

Step 9. $P_{id}^{(t+1)'}$ created from each individual by Gaussian mutation

$$P_{id}^{(t+1)'} = P_{id} + N\left(0, \sigma_i^2\right) \tag{19}$$

$P_{id}^{(t+1)'}$ must satisfy the constraints of prohibited operating zones, ramp-rate limits and generator capacity limits

$$\sigma_i = \beta \times \frac{f_i}{f_{i\min}} \left(P_{i\max} - P_{i\min} \right) \tag{20}$$

where,

$f_{i\ \min}$ -Minimum cost among 'n' trial solutions, β -scaling factor is equal to 0.001 and f_i - Value of the objective function associated with vector P_i.

Step 10. If the evaluation value of each individual is better than the pbest value in step 8 then, the current value is set to be the pbest. If the best pbest among all particles is better than the gbest in step8, then, the value is set to be the gbest.

Step 11. If the number of iterations reaches the maximum go to the step12. Otherwise go to the step 5.

Step 12. The individual that generates the latest gbest is the optimal generation power of each unit with the minimum total generation cost.

5. Results and Discussion

To verify the feasibility of the proposed approach, four different test systems are considered such as three, six, fifteen and twenty units with ramp rate limits and prohibited operating zones constraints. Results of the proposed approach are compared with EP, conventional PSO and 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 the third generation Intel Core i3 processor based personal computer with 4 GB RAM. From the comparison of results, the proposed HPSO method is found to be better in solving the non-linear ED problems.

Test System 1 A three-unit system [36] 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 proposed HPSO method are compared with EP, PSO, GA [36] and 2PNN [37] methods. From the comparison of the results, the fuel cost obtained by the proposed HPSO method is better than the other methods. Fig. 6 shows the comparison of fuel costs for various methods in a three unit systems and Fig. 7 shows the convergence nature of EP, PSO and HPSO methods. From the convergence property, it is evident that the proposed HPSO method has better convergence characteristics than EP and PSO method.

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. The 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 Table 2. The results obtained by the proposed method are compared with EP, conventional PSO, GA [15], DSPSO-TSA [38], BBO [39], HHS [40], HIGA [41] and PSO-GSA [42] methods. From the comparison of results, it clearly shows the proposed HPSO method gives minimum fuel cost than the other methods. Fig. 8 shows the comparison of fuel cost for various methods in a six unit test system and Fig. 9 shows the convergence nature of EP, conventional PSO and proposed HPSO methods.

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

Method	GA	2PNN	EP	PSO	HPSO
P1	194.265	165.00	199.53	190.59	200.18
P2	50.00	113.40	75.68	85.77	76.26
P3(MW)	79.627	34.05	38.19	34.80	34.40
∑Pi(MW)	323.892	312.45	313.40	311.16	310.84
P_L(MW)	24.011	12.45	13.40	11.16	10.84
Fuel Cost($/hr)	3737.16	3652.60	3641.70	3631.1	3623.11

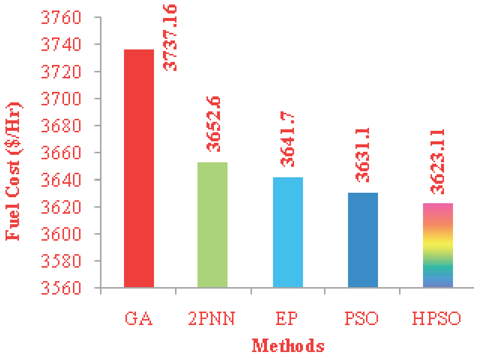

Fig. 6. Comparison of fuel cost for 3 unit system

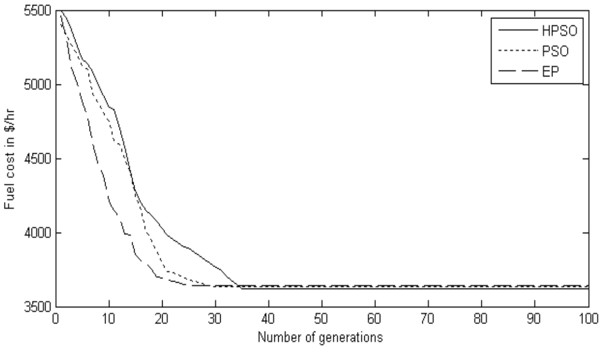

Fig. 7. Convergence of EP, PSO and HPSO

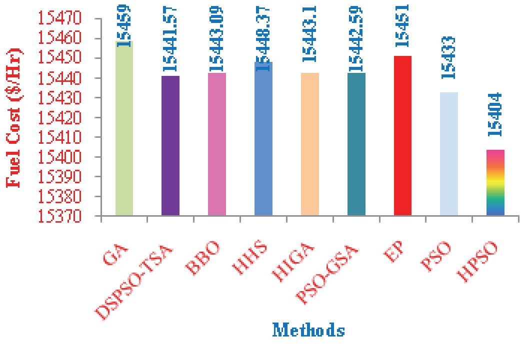

Fig. 8. Comparison of fuel cost for 6 unit system

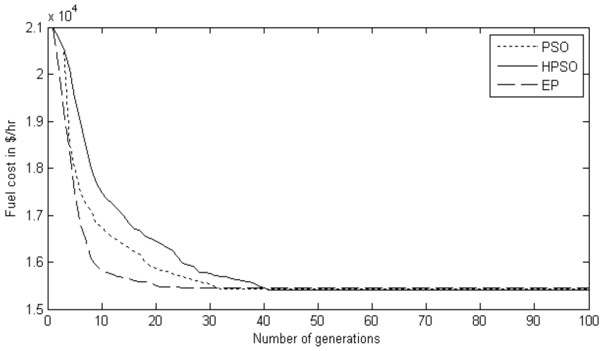

Fig. 9. Convergence of EP, PSO and HPSO

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

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

Method	GA[15]	DSPSO_TS	BBO[39]	HHS[40]	HIGA[41]	PSO-GSA	EP	PSO	HPSO
P1(MW)	474.80	439.29	447.3997	449.9094	447.399	447.5144	431.31	457.26	462.45
P2(MW)	178.63	187.78	173.2392	172.7347	173.241	173.1461	170.33	160.72	184.53
P3(MW)	262.20	261.02	263.3163	262.9643	263.382	263.3337	241.50	247.53	246.60
P4(MW)	134.28	129.49	138.006	136.03	138.98	138.9289	147.98	131.52	108.83
P5(MW)	151.90	171.71	165.4104	166.967	165.392	165.3541	182.64	170.50	171.07
P6(MW)	74.18	86.16	87.0797	86.8778	87.052	87.1269	101.48	106.62	98.50
∑Pi(MW)	1276.0	1275.45	1274.451	1275.483	1275.446	1275.404	1275.24	1274.15	1271.98
P_L(MW)	13.02	13.04	12.446	12.4834	12.446	12.39404	12.24	11.15	8.98
Fuel Cost($/hr)	15459	15441.5	15443.09	15448.37	15443.1	15442.59	15451	15433	15404

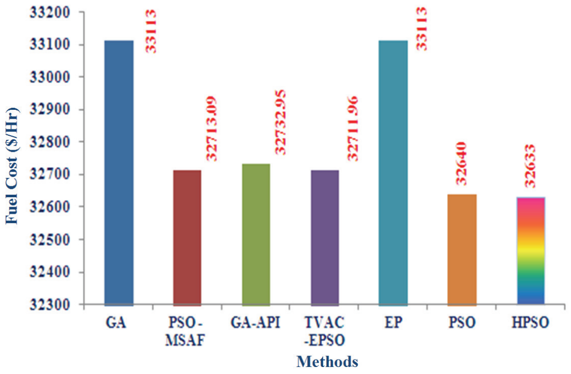

Fig. 10. Fuel cost comparison for 15 unit system

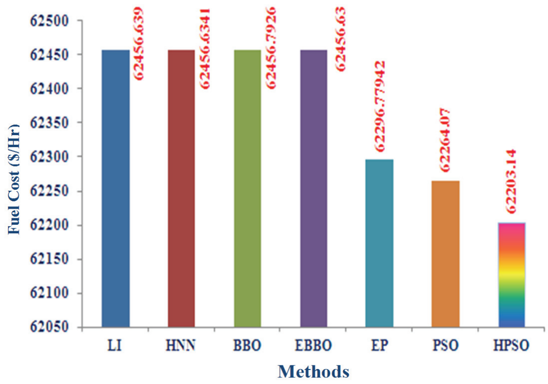

Fig. 12. Fuel cost comparison for 20 unit system

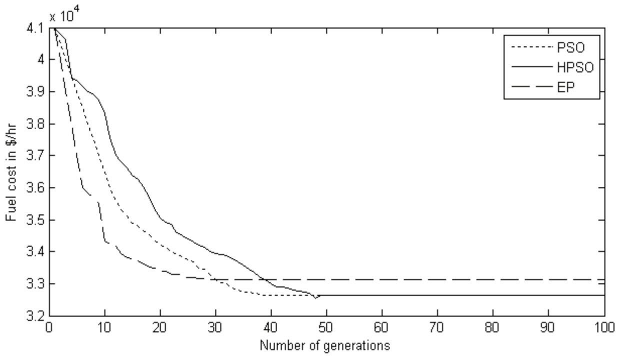

Fig. 11. Convergence of EP, PSO and HPSO

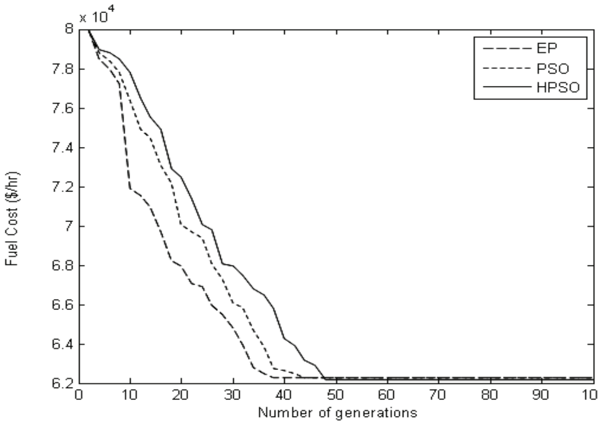

Fig. 13. Convergence of EP, PSO and HPSO

dimension of the population is 100*15 and number of generations is taken as 100. The results obtained by the proposed method is compared with EP, PSO, GA [15], PSO-MSAF [43], GA-AFI [44] and TVAC-EPSO [45] methods and are shown in Table 3. From the comparison of results, it is observed that the proposed HPSO method gives minimum fuel cost than the other methods. Fig. 10 shows the fuel cost comparison for various methods in a fifteen unit test system and Fig. 11 shows the convergence nature EP, PSO and proposed HPSO methods.

Test system 4 The input data for 20 unit test system is taken from [46].The system load demand is 2500 MW. In this test system, the transmission losses, POZ and ramp rate limit constraints are considered. The dimension of the population is 100*20 and the number of generations are100.The results obtained by the proposed method is compared with EP, PSO, Lambda-iteration method [46], Hopfield neural network method [46], BBO [47] and EBBO [48] methods and are shown in Table 4. On comparison of the results, it is evident that the proposed method can provide significant cost saving than other methods.

Fig. 12 shows the fuel cost comparison for various methods for a 20 unit test system and Fig. 13 shows the convergence nature EP, PSO and proposed HPSO methods. It’s evident from the Figs. 7, 9, 11, 13, the proposed HPSO method is free from the shortcoming of premature convergence exhibited by the EP and PSO methods.

6. Conclusion

In this paper, EP, conventional PSO, and proposed

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

Method	GA [15]	PSO-MSAF [43]	GA-API [44]	TVAC-EPSO [45]	EP	PSO	HPSO
P1	415.31	455.00	454.70	455.00	455.00	455.00	455.00
P2	359.72	379.99	380.00	379.96	380.00	380.00	380.00
P3	104.42	130.00	130.00	130.00	116.13	130.00	130.00
P4	74.99	130.00	129.53	130.00	119.06	130.00	130.00
P5	380.28	169.99	170.00	170.00	157.26	150.20	170.00
P6	426.79	459.99	460.00	460.00	460.00	460.00	460.00
P7	341.32	429.99	429.71	430.00	430.00	430.00	430.00
P8	124.79	127.82	75.35	93.02	151.68	60.00	61.72
P9	133.14	33.36	34.96	34.29	52.17	74.01	62.54
P10	89.26	126.34	160.00	160.00	99.11	160.00	160.00
P11	60.06	79.99	79.75	79.17	52.27	80.00	80.00
P12	50.00	80.00	80.00	80.00	65.48	80.00	80.00
P13	38.78	25.00	34.21	25.00	49.77	26.88	25.00
P14	41.94	17.87	21.14	15.00	35.85	21.74	15.00
P15	22.64	15.15	21.02	19.38	34.96	15.00	15.00
$\sum$Pi	2668.40	2660.49	2660.36	2660.83	2658.70	2652.63	2654.26
P_L	38.28	30.49	30.36	30.83	28.74	22.83	24.26
Fuel cost ($/hr)	33113	32713.09	32732.95	32711.96	33113	32640	32633

Table 4. Results of twenty unit system with POZ and RRL

Method	Lambda-Iteration Method [46]	Hopfield Neural Network Method [46]	BBO [47]	EBBO [48]	EP	PSO	HPSO
P1(MW)	512.781	512.78	513.089	513.436	585.2	554.4	584.5
P2(MW)	169.103	169.104	173.353	169.663	108.624	108.624	109.75
P3(MW)	126.89	126.89	126.923	127.474	98.1	97.89	98.1
P4(MW)	102.866	102.866	103.329	103.181	109.24	112.24	110.65
P5(MW)	113.684	113.684	113.774	113.99	79.1	81.082	78.082
P6(MW)	73.571	73.5709	73.0669	73.5092	52.4	52.38	53.78
P7(MW)	115.288	115.288	114.984	115.306	46.78	52.78	45.99
P8(MW)	116.399	116.399	116.424	116.698	78.48	82.48	81.97
P9(MW)	100.406	100.406	100.695	100.752	54.85	53.71	55.71
P10(MW)	106.027	106.027	99.9998	106.26	110.81	114.81	109.18
P11(MW)	150.239	150.24	148.977	150.316	224.8	223.06	225.89
P12(MW)	292.765	292.765	294.021	291.654	498.23	499.23	480.43
P13(MW)	119.115	119.116	119.575	119.333	110.01	115.01	112.87
P14(MW)	30.834	30.8342	30.5479	30.9885	82.88	84.921	86.115
P15(MW)	115.806	115.806	116.455	115.903	99.67	98.67	100.98
P16(MW)	36.2545	36.2545	36.2279	36.2575	23.3	28.3	27.87
P17(MW)	66.859	66.859	66.8594	67.1866	71.5	71.175	63.17
P18(MW)	87.972	87.972	88.547	88.0014	55.21	55.21	52.11
P19(MW)	100.8033	100.803	100.98	101.042	65.516	65.516	67.76
P20(MW)	54.305	54.305	54.2725	51.0917	39.15	40.26	44.77
Σ Pi(MW)	2591.9670	2591.9670	2592.1	2592.041	2593.85	2591.748	2589.677
P_L(MW)	91.9670	91.967	92.1011	92.0414	93.85	91.748	89.677
Fuel Cost ($/hr)	62456.6391	62456.6390	62456.793	62456.63	62296.78	62264.07	62203.14

HPSO are applied successfully to solve the non-linear economic dispatch problems. The proposed HPSO method 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 limits constraints are considered for the selected test systems. The result obtained by the proposed HPSO method is compared with EP, conventional PSO 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 proposed HPSO method can be an alternative approach for finding a better solution for the non linear economic dispatch problems.

References

[1] B.H. Chowdhury and S. Rahman, "A review of recent advances in economic dispatch", IEEE Trans. Power Systems Vol. 5, No. 4, pp. 1248-1259, Nov 1990.

[2] A. J. Wood and B.F. Wollenberg, "Power generation operation and control", 2nd edition, New York Wiley, pp. 29-32, 1996.

[3] JagabondhuHazra and AvinashSinha, "Application of Soft Computing methods for Economic Dispatch in Power Systems", International Journal of Electrical

and Electronics Engineering, Vol. 3, No. 9, pp. 538-543, 2009.

[4] Liang Z.X. and Glover J.D., "A Zoom feature for a Dynamic Programming solution to economic dispatch including transmission losses'" IEEE Transactions on Power Systems Vol. 7 No. 2, pp. 544-549, 1992.

[5] A. J. Selvakumar and K. Thanushkodi, "A new particle swarm optimization solution to non-convex economic dispatch problems", IEEE Trans. Power Systems Vol. 22, No.1, pp. 42-51, Feb 2007.

[6] Wong K.P and Fung C.C, "Simulated annealing based economic dispatch algorithm, "IEE proceedings Generation, Transmission and Distribution Vol.140, No. 6, pp. 509-515, 1993.

[7] I. N Desilva, L. Nepomuceno and T. M. Basdo "Designing a modified Hopfield Network to solve an ED problem with non-linear cost function", proceeding Int. conf on Neural networks, Vol. 2, pp. 1160-1165, May 2002.

[8] G. Baskar, N. Kumarappan and M. R. Mohan, "Optimal Dispatch using Improved Lambda based Genetic algorithm suitable for utility system", Int. journal on Electric Power components and systems, Vol. 31, pp. 627-638, June 2003.

[9] H.T. Yang, P.C. Yang and C.L. Huang, "Evolutionary programming based economic dispatch for units with non-smooth fuel cost functions", IEEE Trans. on Power Systems Vol. 11, pp. 112-118, Feb 1996.

[10] K. P. Wong and J. Yuryevich, "Evolutionary program based algorithm for environmentally- constrained economic Dispatch ", IEEE Trans. Power System Vol. 13, pp. 301-306, May 1998.

[11] X. Yao, Y. Liu and G. Lin, "Evolutionary Programming made faster", IEEE Trans. Evol. Comput Vol. 3, pp. 82-102, July 1999.

[12] Jayabharathi. T, Sadasivam G, and Rama chandran V," Evolutionary Programming based economic dispatch of generators with prohibited operating zones" Electric Power System Research, Vol. 52, pp, 261-266, 1999.

[13] Jayabharathi T., Jayaprakash. K, Jeyakumar D. N. and Raghunathan. T, "Evolutionary Programming Techniques for different kinds of Economic dispatch problems," Electric Power Systems Research Vol. 73, pp. 169-176, 2005.

[14] Lin W. M, Cheng F.S and Tsay M. T, "An improved Tabu search for economic dispatch with multiple minima," IEEE Trans. on Power Systems Vol. 17, No. 1, pp. 108-112, 2002.

[15] Zwe-Lee Gaing "Particle Swarm Optimization to solving the Economic Dispatch considering the generator constraints", IEEE Trans. on Power Systems Vol. 18, No. 3, pp. 1187-1195, Aug 2003.

[16] J. B. Park, K. Lee, J. Shin and K. Y. Lee "A particle swarm optimization for economic dispatch with non-smooth cost functions", IEEE Trans. on Power Systems Vol. 20, No. 1, pp. 34-42, Feb,2005.

[17] D. N. Jeyakumar, T. Jayabarathi and T. Raghunathan "A Particle Swarm Optimization for various types of economic dispatch problems," International journal on Electric Power and Energy System Vol. 28, No. 1, pp. 36-42, Jan 2006.

[18] M.R. Alrashidi and M. E. EI- Hawary," A Survey of Particle Swarm Optimization applications in power system operations," Electric Power components and systems Vol. 34, No. 12, pp. 1349-1357, Dec 2006.

[19] Chun-Lung Chen, Rong-Mow Jan, Tsung-Ying Lee and Cheng-Hsiung Chen," A novel particle swarm optimization Algorithm solution of Economic Dispatch with Valve Point Loading", Journal of Marine Science and Technology, Vol. 19, No. 1, pp. 43-51, 2011.

[20] Zong woo Geem "Economic Dispatch Using Parameter-Setting_Free Harmony Search" journal of Applied Mathematics, Vol. 2013, pp. 1-5, 2013.

[21] Subbaraj P, Rengaraj R and Salivahanan S., "Enhancement of Combined heat and power economic dispatch using Self adaptive real coded genetic algorithm". Applied Energy, Vol. 86, pp. 915-921, 2009.

[22] Mohammadi-Ivatloo B, Rabiee A, Soroudi A and Ehsan M "Iteration PSO with time varying acceleration coefficient for solving non- convex economic dispatch problems" Electrical Power and Energy Systems, Vol. 42, pp. 508-516, 2012.

[23] Y.H. Shi and R.C. Eberhart, "Fuzzy Adaptive particle swarm optimization", in Proc. of the IEEE Congress on Evolutionary Computation, Vol. 1, Seoul Korea, pp. 101-106, 2001.

[24] Y.H. Shi and R.C. Eberhart, "A modified particle swarm optimizer", in Proc. of the IEEE Congress on Evolutionary Computation, IEEE Service Center, USA pp. 69-73, 1998.

[25] Y.L. Zhang, L.H. Ma, L.Y. Zhang and J.X. Qian, "On the Convergence Analysis and Parameter Selection in Particle Swarm Optimization", in Proc. Int. Conf. on Machine learning and Cybernetics. Zhejiang University, Hangzhou, China, pp. 1802-1807, 2003.

[26] R.C. Eberhart and Y.H. Shi, "Tracking and optimizing dynamic systems with particle swarms", in Proc. of the IEEE Congress on Evolutionary Computation, San Francisco, Cailf, USA, pp. 94-100, 2001.

[27] L. P. Zhang, H. J. Yu, D. Z. Chen and S. X. Hu, "Analysis and improvement of particle swarm optimization algorithm", Information and Control, Vol. 33, pp. 513-517, 2004.

[28] Kuo, C. C. "A novel coding scheme for practical economic dispatch", IEEE Trans on Power System. Vol. 23, No. 4, pp. 1825-1835, Nov. 2008.

[29] S.K. Wang, J.P. Chiou, and C.W. Liu, "Non-smooth / non-convex economic dispatch by a novel hybrid differential evolution algorithm", IET Gen., Transm.,

Distribution, Vol. 1, No. 5, pp. 793-803, 2007.

[30] Chiou, J. P, "Variable scaling hybrid differential evolution for large scale economic dispatch problems". Elect. Power System Research, Vol. 77, No. 1, pp. 212-218, 2007.

[31] Chiang, C-L. "Genetic -based algorithm for power economic load dispatch", IET Gen., Transm., Distribution, Vol. 1, No. 2, pp. 261-269, 2007.

[32] Mariani V.C., and L.D.S. Coelho, "Particle swarm approach based on quantum mechanics and harmonic oscillator potential well for economic load dispatch with valve-point effects", Energy Converse. Management. Vol. 49, No. 11, pp. 3080-3085, 2008.

[33] K.T. Chaturvedi, M. Pandit and L. Srivastava, "Self-Organizing hierarchical particle swarm Optimization for nonconvex economic dispatch", IEEE Trans on Power System Vol. 23, No. 3, pp. 1079-1087, Aug 2008.

[34] Pandi B.K and Panigrahi V.R, "Bacterial foraging optimization; Nelder-Mead hybrid algorithm for economic load dispatch", IET Gen., Transm., Distribution, Vol. 2, No. 4, pp. 556-565, 2008.

[35] Nidul Sinha, R. Chakrabarti and P. K. Chattopadhyay "Evolutionary Programming Techniques for Economic Load Dispatch", IEEE Trans. on Evolutionary Computation, Vol. 7, No. 1, pp. 83-94, Feb 2003.

[36] Chen P-H and Chang H-C, "Large scale economic dispatch by genetic algorithm", IEEE Trans.on Power Systems Vol. 10, No. 4, pp. 1919-1926, 1995.

[37] Naresh. R, Dubey J and Sharma J, "Two-phase neural network based modeling frame work of constrained economic load dispatch", IEE proce. Generation, Transmission, Distribution, Vol. 151, No. 3, pp. 373-378, 2004.

[38] Khamsawang, and S. Jiriwibhakorn, "DSPSO-TSA for economic dispatch problem with non smooth and non continuous cost functions", Energy Conversation Management Vol. 51, pp. 365-375, 2010.

[39] Bhattacharya A, Chattopadhyay P. K, "Bio geography Based Optimization for different economic load dispatch problems", IEEE Trans. on power Systems Vol. 25, No. 2, pp. 1064-1077, 2010.

[40] Pandi V. R, Panigrahi B. K, Bansal R. C, Das S, Mohapatra A, "Economic Load Dispatch using Hybrid Swarm Intelligence Based Harmony search Algorithm", Electric power components and systems, Vol. 39, No. 8, pp. 751-767, 2011.

[41] Mir.Mahmood Hosseini,, Hamidreza ghorbani, A. Rabii, Sh. Anvari" A novel Heuristic Algorithm for solving Non-convex Economic Load Dispatch problem with Non-smooth cost function", Journal of Basic and Applied Scientific Research, Vol. 2, No. 2 pp. 1130-1135, 2012.

[42] Hari Mohan Dubey, Manjaree Pandit, B. K. Panigrahi Mugdha Udgir, "Economic Load Dispatch by Hybrid Swarm Intelligence Based Gravitational Search Algorithm", I. J Intelligent Systems and Applications, Vol. 08, pp. 21-32, 2013.

[43] P. Subbaraj, R. Rengaraj S. Salivahanan and T.R. Senthilkumar, "Parallel Particle Swarm Optimization with modified stochastic acceleration factors for solving large scale economic dispatch problem", International journal of Electrical Power and Energy Systems Vol. 32, pp. 1014-1023, 2010.

[44] I.Ciornei and E. Kyriakides," A GA-API solution for the Economic Dispatch of Generation in Power System Operation", IEEE Transaction on Power System, Vol. 27, pp. 233-242, 2012.

[45] Mohd Noor ABDULLAH, Nasrudin Abd RAHIM, Abd Halim Abu BAKAR, Hazlie MOKHLIS, Hazlee Azhil ILLIAS, Jasrul Jamani JAMIAN, "Efficient Evolutionary Particle Swarm Optimization Approach for Non convex Economic Load Dispatch Problem", PRZEGLAD ELEKTROTECHNICZNY, R 89 NR 2a pp. 139-143, 2013.

[46] Ching-Tzong Su and Chen -Tung Lin, "New Approach with a Hopfield Modelling Frame work to Economic Dispatch" IEEE trans on power system, Vol. 15, No. 2, pp. 541-545, 2000.

[47] Bhattacharya A and Chattopadhyay, "Biogeography-Based Optimization for different economic load dispatch problems" IEEE Trans on power systems, Vol. 25, No. 2, pp. 1064-1077, 2010.

[48] Vanitha M and Thanuskodi K, "An Effective Biogeography Based Optimization Algorithm to solve Economic Load Dispatch Problems", Journal of computer sciences, Vol. 8, No. 2, pp. 1482-1486, 2012.

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