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Tabu Search Enhanced Artificial Bee Colony Algorithm to Solve Economic Load Dispatch with Prohibited operating zones and Ramp Rate Limit Constraints

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ABSTRACT

This paper proposes a new Tabu Search Enhanced Artificial Bee Colony (TSEABC) algorithm that integrates the concepts of Tabu Search (TS) and Artificial Bee Colony (ABC) techniques. The proposed algorithm is applied to solve Economic Load Dispatch(ELD) problems considering of prohibited operating zones and ramp rate limits of thermal units, capacity limits and power balance constraints. In the proposed TSEABC algorithm, the best attributes of both TS and ABC are utilized, and it is capable of finding the better optimal solution for the combinatorial optimization problems. For validating the proposed algorithm, it has been tested on the standard three, six and fifteen unit test systems. The comparison of results show that the proposed TSEABC algorithm is well suitable for solving non-linear economic dispatch problems, and it is doing better than the EP, PSO and other modern metaheuristic optimization methods reported in the recent literatures.

1. Introduction

The power needs of this world increases day-by-day and scarcity of energy resources and increasing power generation costs are inevitable in today's power system. The most important power system planning problem in modern power system operation is scheduling of generation and economic dispatch.

The primary aim of unit commitment is to find the on/off status of all the available generating units and fixing the power output level of all the on state units in a particular time horizon so that the total production cost is minimum. The most important objective of the economic dispatch problem in the power system is to find the optimal power output of generating units that minimizes the total fuel cost while satisfying the system constraints [1]. In the past few decades, traditional methods such as Lambda iterative method, Newton's method, branch and bound technique, Gradient search method, Linear and quadratic programming methods, Interior point method and Dynamic programming method have been used to get the solution for economic load dispatch(ELD) problems [2]. The above methods solved the ELD problem based on the assumption that the fuel cost equations of generating units are quadratic or cubic in nature. Due to the presence of prohibited operating zones and ramp rate limit constraints, the input-output characteristics of generating units are highly non-linear in nature. Due to its simplicity in implementation, the Lambda-iteration method has been applied for solving ELD problems.

Since the lambda iteration method requires a continuous fuel cost equations, it cannot be directly applied to ELD problems with discontinuous prohibited operating zones. Newton's method is very sensitive for the selected values of initial conditions[3]. The presence of inequality constraints makes Gradient search difficult to converge. Linear programming method provides better solution in less processing time but results are not accurate due to linearization of the mathematical model. The criterion for step size selection in Interior point method is very important to get better solution but which needs expert knowledge in the above selection [3].

Among the conventional methods available, Dynamic Programming (DP) method is best technique for solving the ELD problems with non-convex and unit cost functions. But dimensionality issues and local convergence are main issues to be addressed in the DP approach [4]. All the conventional techniques are assuming that the cost curve is continuous and monotonically increasing.

Due to the presence of equality and inequality constraints and prohibited operating zones ED problem is practically non-linear and non-convex optimization problem with multiple local optimal points in the solution space [5]. To overcome the issues of conventional techniques for solving ED problems, the power engineers propose meta-heuristic algorithms such as 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]. But the above methods cannot guarantee global optimal solution for highly nonlinear combinatorial optimization problems.

The simulated annealing technique is working on the basis of annealing process in the metals but the performance of SA is affected by improper selection of annealing temperature. In Hopfield Neural network approach,

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the training data required and accuracy of training data are key issues to be addressed. Recently many researchers are using GA for solving nonlinear optimization problems but GA is successful in locating high performance area in the solution space but faces difficulty in exactly locating the optimal solution [15]. If binary coded GA is used, the process of encoding and decoding makes the simple GA more complicated [19]. Evolutionary programming technique for ELD problem is more competent than GA method in computation time and can generate a high-quality solution with less computational effort. The particle swarm optimization algorithm is a latest algorithm in the class of swarm intelligence and has a character of parallel search capability, so it has more possibility of determining the global (or) near global optimal solution for the non-linear ELD problems. The premature convergence of PSO while handling the problems with highly nonlinear solution space is the main drawback of PSO [19]. The proper selection of parameters and weighting factor is another drawback in PSO implementation.

In recent years, power engineers propose integrated algorithms which combines the best features of two or more algorithms for solving nonlinear problems. Some of the hybrid algorithms such as Simulated Annealing-Particle Swarm Optimization (SA-PSO) [20], Self Tuning Hybrid Differential Evolution (STH DE)[21],Variable Scaling Hybrid Differential Evolution (VSHDE) [22], Improved Genetic Algorithm with Multiplier Updating (IGAMU) [23] , Quantum-inspired version of the PSO using the harmonic oscillator(HQPSO) [24], Self-Organizing hierarchical Particle Swarm Optimization (SOH-PSO) [25], and Bacterial Forging with Nelder-Mead Algorithm (BFA-NM) [26] are reported in the literature.

In this paper, a new approach called Tabu Search Enhanced Artificial Bee Colony (TSEABC) algorithm is proposed to solve non-linear ELD problems taking into account of power balance constraint, generator operating limits, ramp rate limits and prohibited operating zones. In the proposed algorithm, the promising features of both TS and ABC are exploited to avoid the shortcomings in other meta-heuristic methods. The proposed TSEABC algorithm is presented to increase the possibility of exploring the search space where the global optimal solution exists and improving the convergence characteristics.

The main objective of the present work is to develop a integrated algorithm which will be suitable for larger combinatorial and nonlinear systems and to avoid premature convergence. The results obtained by the proposed algorithm for the test cases are compared with other methods which are reported in the recent literature such as

1. Evolutionary programming [27].
2. Conventional particle swarm optimization [15].
3. Proposed hybrid PSO method [HPSO].

The performance of the proposed algorithm has been investigated on three test cases, and the results are tabulated for comparison with other algorithms reported in the literature.

2. Problem formulation

The aim of ELD problem is to curtail 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 ELD is multimodal, non-differentiable and highly non-linear. Mathematically, the problem can be stated as in (1) [2, 20]

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

i = 1, 2, 3,……….., 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

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

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

2.1 Real power balance constraint

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

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

The total transmission loss (P_L) can be expressed in a quadratic function of power generation using B_{mn} coefficient matrix.

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

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 generating unit i should be within its maximum and minimum limits of real power generation and is given by

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

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 of power generation called prohibited operating zones where operation is restricted due to the physical limitation of steam valve, component, vibration in shaft bearing etc., Due to the presence of poz, there will be discontinuities in fuel cost curve and converts the constraint as below

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

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)

2.4 Ramp rate limit constraints

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

(i) As generation increases (up ramp)

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

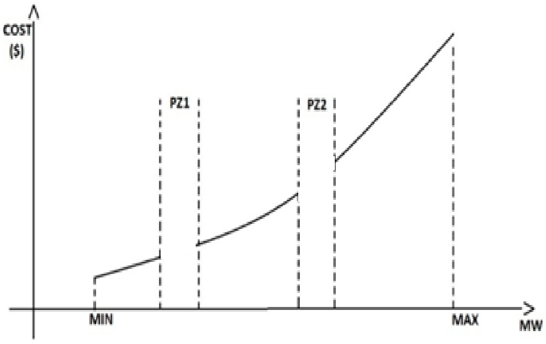

Fig 1. Schematic of Prohibited operating zones.

(ii) As generation decreases (down ramp)

$$P_{i(t-1)} - P_{i(t)} \leq DR_i \quad (8)$$

Therefore the generator power limit constraints can be modified as

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

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.

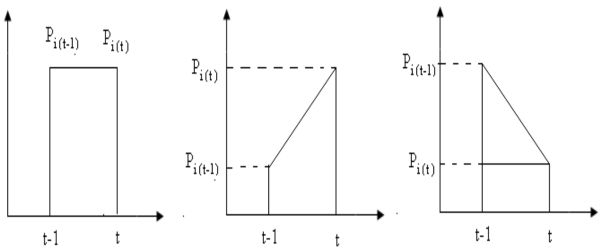

Fig. 2. Ramp rate limits of generating units

4. Overview of Artificial Bee Colony Algorithm

The meta heuristic algorithms are developed by imitating swarm intelligence techniques for solving nonlinear optimization problems. The degree of intellect of insects is based on the frequency of interaction between the insects. Dervis Karaboga developed ABC algorithm by his inspiration from the bee colonies found in the nature. (Karaboga D, 2005). ABC algorithm is based on the interaction between the various types of bees found in nature. There are three different types of bees in a bee colony system such as scout bee, employed bee and onlooker bee. The onlooker bees will have an exchange of information with employed bees to select a direction. In a colony each group of bees have different types of food searching tactics. The nectar is defined as quantum food source collected by the bees where as the aptness is food source collected by each bee in a colony. The bees will interact with each other during food search through waggle dance. (Karaboga and Basturk, 2007). The employed bees will share the information such as the direction of food source and quantum of nectar with the onlooker bees during the waggle dance performed. Scout bee is otherwise called as queen bee will search food on its own without any prior knowledge about the food location. In the initial population of bee colony all the bees generated randomly but made feasible by checking all the constraints. Through the processes of shift neighbourhood and double shift neighbourhood each employed will be up dated. The current position of employed bees is updated and the new aptness will be calculated. Once employed bees made their modification process, the unemployed bees complete the adaptation of location through group mates in the colony. In each cycle, the quality of the food source is compared between the bees and the best source will be stored in the memory location. After the maximum cycle number, the best member available in the memory is termed as optimal solution. The proposed TS enabled ABC (TSEABC) algorithm integrates the best features of Artificial bee colony algorithm and tabu search based on short term memory and is applied for solving the economic dispatch problems with prohibited operating zones and valve point loading. The procedure of searching the optimal solution by TSEABC algorithm is given as flow steps as shown in fig.3.

4.1 Proposed TS enhanced ABC algorithm

The proposed TSEABC algorithm has the following algorithmic steps for solving any general optimization problem.

1. Initialize the parameters of proposed tabu search enhanced ABC algorithm
2. Using Greedy Randomized Adaptive Search Heuristics (GRAH) algorithm, generate initial employed bee colony population
3. Evaluate the fitness function for each bee in the initial population
4. Set iteration count I=0
5. Loop 1
6. Set N=0
7. Loop 2

a. Do shift neighbourhood
b. Do double shift neighbourhood
c. Using the fitness function of bees, determine the probabilities
d. From the calculated probabilities above, allocate unemployed (onlooker) bees to employed bees.
e. For all unemployed (onlooker) bees apply Ejection-Chain neighbourhood
f. Calculate fitness values for each unemployed bee, find best onlooker bee, replace with respective employed bee if fitness(best onlooker) < fitness (employed)
g. Identify best feasible onlooker bee, replace with best solution if fitness (best feasible onlooker) < fitness (best)
h. N = N+1

8. Go to step 7 until N= employed bee
9. Apply tabu list and logical aspiration criterion to generate and check the neighbour solution points to the best employed bee in the population in more promising region of solution space.
10. I = I+1
11. Go to step 5 until I = Max. cycle number is reached.

4.2 Implementation of TSEABC algorithm for economic dispatch with POZ and ramp rate limts

The details of the implementation of important steps in the proposed algorithm are summarized here as follows:

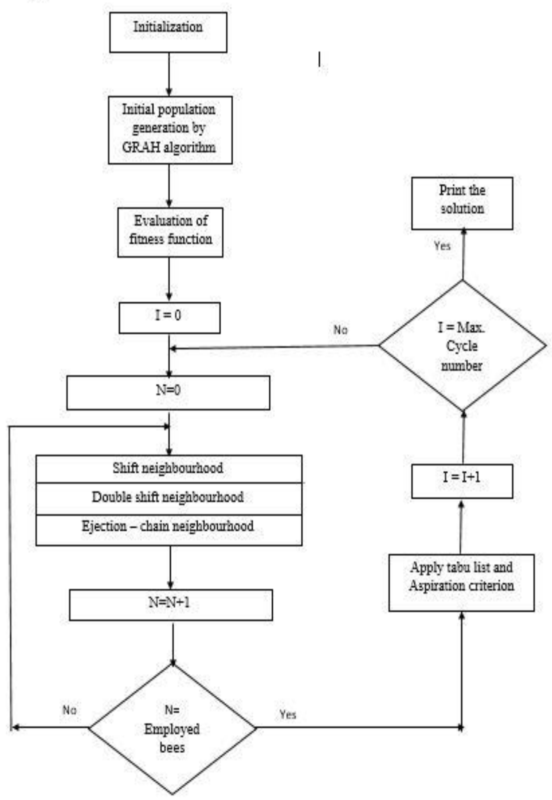

Fig 3. General flowchart of TSEABC algorithm

Step 1: Initialization

Initialize the parameters of the ABC algorithm and tabu search such as colony size, number of employed bees, number of onlooker bees, maximum iteration number, length of ejection chain neighbourhood and tabu list size and aspiration criterion for solving the economic dispatch problem with prohibited operating zones and ramp rate limits.

Step 2: Coding of solution and Generation of Initial population

A row matrix with number of units as the column size has been used as solution for the problem. A real coding has been used in the TSEABC algorithm. Each bee in the colony is converted into one row vector of N decimal numbers (P_1, P_2, …P_N), each represents the schedule of one unit for time duration T. Accordingly, a bee colony size of NCOL is stored in a matrix NCOL X N (Kit Po Wong and Jason Y Uryevich, 1998). The number of bees in the colony is represented by NCOL. Initial population of employed bee colony is generated by GRAH algorithm which considers the initial condition of each unit, ramp rate limits and prohibited operating zones. Since the initial population satisfies the essential constraints of ELD problem with POZ and RRL constraints, each bee in the colony is feasible candidate solution for the proposed problem.

Step 3: Evaluation of Fitness function

The objective function used in the ELD problem is minimization of fuel cost provided all the constraints are satisfied including POZ and RRL constraints.

Step 4: Neighbourhood Structures

Shift neighbourhood is done by changing the bit position of any one unit of each candidate solution. A special case of long chain neighbourhood is called double shift neighbourhood in which two shift moves are performed. Swap neighbourhood is the important operation in double shift neighbourhood which is the interchange of windows between the candidate solutions.

Once the process of neighbourhood structures completed, the probabilities of bees can be determined from the fitness values of bees by the formula

$p_i = \Sigma\ (1 / \text{fitness}_i) / \text{fitness}_i$

The number of onlooker bees will be decided from the calculated probabilities above and will be sent to food sources of employed bees. The ejection-chain neighbourhood is applied for all the onlooker bees and the fitness value has been evaluated for all the onlooker bees. The best onlooker bee will replace the respective employed bee if fitness(best onlooker) < fitness (employed) and the best feasible onlooker bee is selected (Shrivastava *et al*., 2015). The process is continued till N reaches the predefined number of employed bee.

Step 5: Tabu Array and Logical Aspiration factor

The tabu array is an idea in tabu search to prohibit the revisiting of already explored solution points in the search space (Fred Glover and Manuel Laguna, 1997). These prohibited moves are tabulated in a separate array and named as tabu. The tabu search based on short term memory has been applied for searching the more hopeful region of the solution space identified by the ABC algorithm. The quality of the solution is affected by the dimension of tabu array. In the search process, some moves in the tabu array may be overruled with the help of aspiration factor. Many types of aspiration factor are used in the literature. The suitable type of aspiration factor for ELD problem with POZ and RRL constraints is logical aspiration factor. If a move in a search process gives better objective function value than the one got earlier with the similar move, priority will be given to the move with better objective function with the help of logical aspiration factor. Aspiration factor adds elasticity in the tabu search part of the TSEABC algorithm and hence smart progress in the search is always ensured. This is called overruling of tabu status.

5. Results and discussion

To verify the feasibility of the proposed algorithm, three different test cases are considered such as three, six and fifteen units with ramp rate limits and prohibited operating zone constraints. Results of the proposed algorithm are compared with EP, conventional PSO and other methods, which are presented in the literatures. 50 trails runs were performed and observed the variations during the search process to reach convergence characteristics and optimal solutions. The B_{mn} loss formula coefficient matrix of power system network was used to calculate the total transmission losses. A software package has been developed in MATLAB and executed on the Intel Core i3 processor based personal computer with 4 GB RAM. From the comparison of results, the proposed algorithm is found to be better in solving the non-linear ED problems.

Test System 1 A three-unit system is considered from ref [28]. The system load demand is 300MW. The parameter selection for the proposed algorithm is shown in table 1.

The dimension of population is 100x3 because there are 100 bees in the colony with 3 generators in the example system. The test system has been solved by the proposed algorithm and results are tabulated in table 2. The results of the proposed TSEABC algorithm are compared with PSO [38], HPSO [38], GA [28] and 2PNN [29] methods. From the comparison of the results, the fuel cost obtained by the proposed TSEABC algorithm is better than the other methods. Figure 4 shows the comparison of fuel costs for various methods in a three unit systems and Figure 5 shows the convergence characteristics of the proposed TSEABC algorithm.

Test system 2: The system which has six thermal units, 26 buses and 46 transmission lines has been taken from ref [15]. The load demand is 1263MW. The dimension of the population is 100x6 and maximum cycle number is 500. 50 trial runs were conducted and the best solutions are shown in table 3. The results obtained by the proposed TSEABC algorithm are compared with EP, conventional PSO, GA [15], DSPSO-TSA [30], BBO [31], HHS [32], HIGA [33], PSO-GSA [34] and HPSO [38] methods. From the comparison of results shown in fig, it clearly shows the proposed TSEABC algorithm gives minimum fuel cost than the other methods.

Figure 6 shows the comparison of fuel cost for various methods in a six unit test system and Figure 7 shows the convergence characteristics of the proposed TSEABC algorithm.

Test system 3: The input data of 15 unit test system is 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_{mn} loss formula coefficient matrix. The dimension of the population is 100x15 and maximum number of cycles is taken as 500. The results obtained by the proposed method is compared with HPSO [38], PSO [38], GA [15], PSO-MSAF [35], GA-AFI [36] and TVAC-EPSO [37] methods and are shown in Table 4. From the comparison of results, it is observed that the proposed TSEABC algorithm gives minimum fuel cost than the other methods.

Figure 8 shows the fuel cost comparison for various methods in a fifteen unit test system and Figure 9 shows the convergence characteristics of the proposed algorithm. It's evident from the illustrations that the proposed TSEABC algorithm is free from the shortcoming of premature convergence exhibited by the EP, PSO and HPSO methods.

Table 1. Parameter selection.

Parameter	Chosen value
Population Size of bee colony	100
Maximum cycle number (I)	500
Number of employed bees (N)	30
Number of onlooker bees (M)	70
Number of scout bees	3
Tabu list size	10

Table 2. Results of three unit system with POZ & RRL.

Method	GA [28]	2PNN [29]	PSO [38]	HPSO [38]	TSEABC
P1(MW)	194.265	165.00	199.53	200.18	199.88
P2(MW)	50.00	113.40	75.68	76.26	76.44
P3(MW)	79.627	34.00	39.22	34.40	34.40
∑Pi(MW)	323.892	312.45	313.40	310.84	310.72
P_L(MW)	24.011	12.45	13.40	10.84	10.72
Fuel Cost($/hr)	3737.16	3652.60	3641.70	3623.11	3621.2

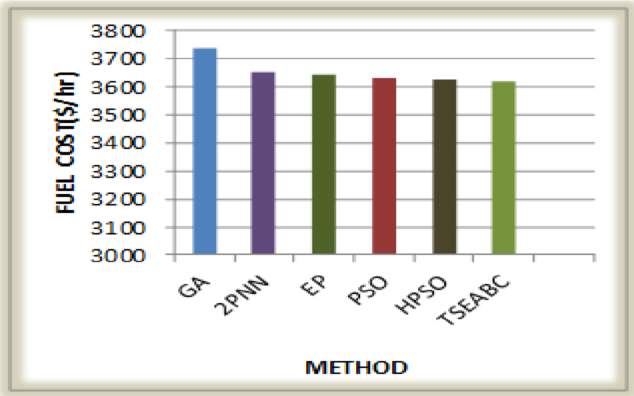

Fig 4. Comparison of fuel cost for 3 unit system.

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

Method	GA[15]	DSPSO_TSA [30]	BBO[31]	HHS[32]	HIGA[33]	PSO-GSA [34]	PSO [38]	HPSO [38]	TSEABC
P1(MW)	474.80	439.29	447.3997	449.9094	447.399	447.5144	457.26	462.45	461.95
P2(MW)	178.63	187.78	173.2392	172.7347	173.241	173.1461	160.72	184.53	185.02
P3(MW)	262.20	261.02	263.3163	262.9643	263.382	263.3337	247.53	246.60	246.11
P4(MW)	134.28	129.49	138.006	136.03	138.98	138.9289	131.52	108.83	109.08
P5(MW)	151.90	171.71	165.4104	166.967	165.392	165.3541	170.50	171.07	171.47
P6(MW)	74.18	86.16	87.0797	86.8778	87.052	87.1269	106.62	98.50	98.10
∑Pi(MW)	1276.0	1275.51	1275.446	1275.487	1275.446	1275.394	1274.1	1271.9	1271.98
P_L(MW)	13.02	13.04	12.446	12.4834	12.446	12.39404	11.15	8.98	8.56
Fuel Cost($/hr)	15459	15441.5	15443.09	15448.37	15443.1	15442.59	15433	15404	15401

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

Method	GA [15]	PSO-MSAF [35]	GA-API [36]	TVAC-EPSO [37]	PSO [38]	HPSO [38]	TSEABC
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	130.00	130.00	130.00
P4	74.99	130.00	129.53	130.00	130.00	130.00	130.00
P5	380.28	169.99	170.00	170.00	150.20	170.00	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	60.00	61.72	62.00
P9	133.14	33.36	34.96	34.29	74.01	62.54	62.26
P10	89.26	126.34	160.00	160.00	160.00	160.00	160.45
P11	60.06	79.99	79.75	79.17	80.00	80.00	79.55
P12	50.00	80.00	80.00	80.00	80.00	80.00	79.42
P13	38.78	25.00	34.21	25.00	26.88	25.00	25.28
P14	41.94	17.87	21.14	15.00	21.74	15.00	15.00
P15	22.64	15.15	21.02	19.38	15.00	15.00	15.00
∑Pi	2668.40	2660.49	2660.36	2660.83	2652.63	2654.26	2653.96
P_L	38.28	30.49	30.36	30.83	22.65	24.26	23.96
Fuel cost ($/hr)	33113	32713.09	32732.95	32711.96	32640	32633	32621

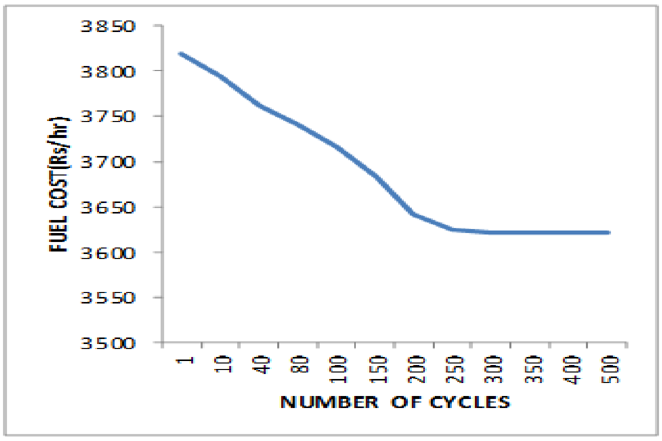

Fig 5. Convergence of proposed TSEABC algorithm (Test case-1).

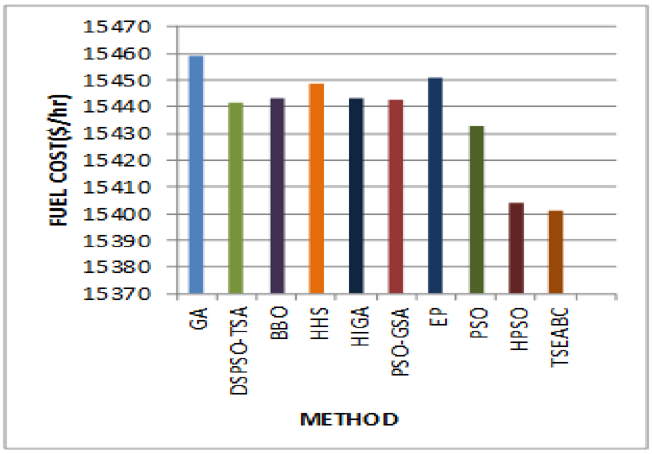

Fig. 6. Comparison of fuel cost for 6 unit system.

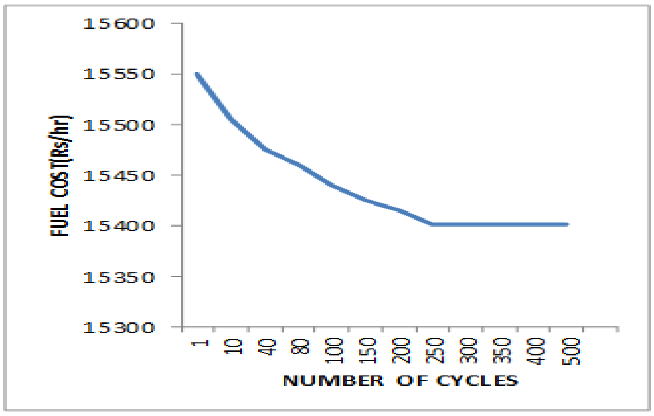

Fig. 7. Convergence of proposed TSEABC algorithm (Test case-2).

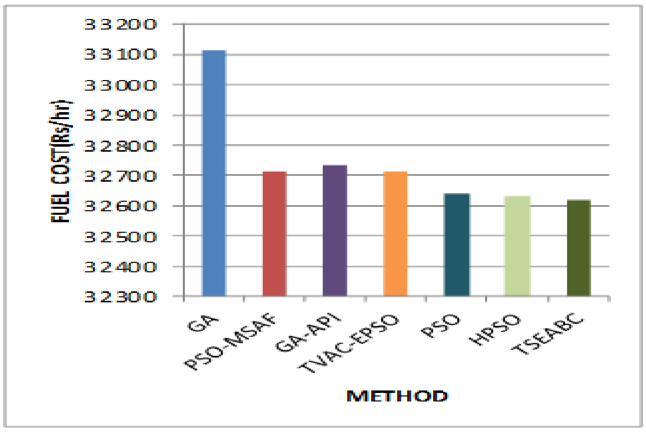

Fig 8. Comparison of fuel cost for 15 unit system.

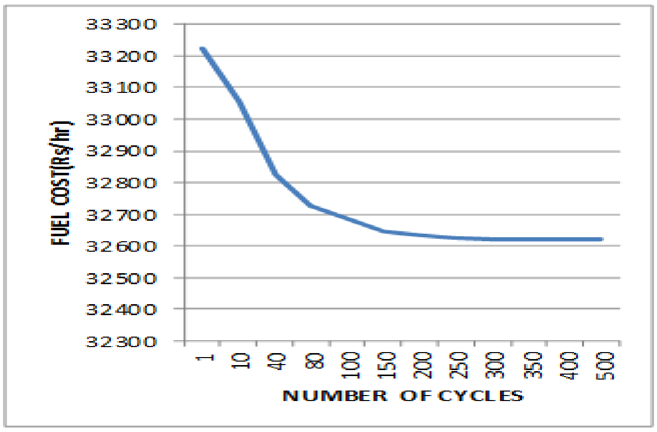

Fig 9. Convergence of proposed TSEABC algorithm (Test case-3).

6. Conclusion

In this paper, tabu search enhanced artificial bee colony algorithm has been successfully applied to solve the non-linear economic dispatch problems. The proposed TSEABC algorithm 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 solution obtained by the proposed TSEABC algorithm is compared with PSO, HPSO and other methods reported in recent literatures. Based on the fuel cost comparison, the methods have been compared. From this study, it can be accomplished that the proposed TSEABC algorithm can be an alternative approach for finding a better solution for the non linear economic dispatch problems.

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