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# Teaching learning based optimization for economic load dispatch problem considering valve point loading effect

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ABSTRACT

This paper presents a novel teaching learning based optimization (TLBO) technique to solve economic load dispatch (ELD) of the thermal unit without considering transmission losses. The proposed methodology can take care of ELD considering nonlinearity such as valve point loading. The objective of economic load dispatch is to determine the optimal power generation of the units to meet the load demand, such that the overall cost of generation is minimized, while satisfying different operational constraints. TLBO is a recently developed evolutionary algorithm based on two basic concepts of education namely teaching phase and learning phase. At first, learners improve their knowledge through the teaching methodology of teacher and finally learners increase their knowledge by interactions among themselves. The effectiveness of the proposed algorithm has been verified on three different test systems with equality and inequality constraints. Compared with the other existing techniques demonstrates the superiority of the proposed algorithm.



## Introduction

Recently the electrical power market becomes more competitive. In order to survive in this situation, the optimal power generation is required which minimize the total cost. Economic load dispatch determines low cost operation of a power system by dispatching the power generation resources to supply the load. The main objective of the ELD is to minimize the total cost of generation while satisfying the operational constraints.

In the traditional ELD problem, the cost function for each generator has been presented by a quadratic function and is solved using mathematical programming based optimization techniques such as lambda iteration method and gradient-based method [1]. Basu proposed artificial bee colony optimization technique to solve economic dispatch problem considering transmission losses, multiple fuels, etc. [2]. Problems of economic load dispatch including transmission losses are solved using dynamic programming method [3]. But there was a problem of 'curse of dimensionality' or local optimality. To overcome this problem several alternative methods are developed such as differential evolution, tabu search, and particle swarm optimization. Economic Load Dispatch that includes wind power has been solved using quantum genetic algorithm [4]. Pothiya et al. proposed a novel and efficient optimization approach based on ant colony optimization for solving the economic dispatch problem with non-smooth cost functions [5]. An efficient chaotic self-adaptive differential harmony search algorithm is proposed to solve the complicated dynamic economic dispatch problem including valve point effect, ramp rate limits and prohibited operating zone [6]. An integrated algorithm based on evolutionary programming and simulated annealing is developed for solving ELD problem in [7]. Hota et al. presented a newly developed optimization approach involving a modified bacterial foraging algorithm to solve economic load dispatch problem [8]. Multiple tabu search algorithm is used to solve the economic dispatch problem by taking valve-point effects into consideration [9]. Enhanced cross-entropy method is also proposed to solve dynamic economic dispatch problem with valve-point effects [10]. In [11], Meng proposed quantum-inspired particle swarm optimization to solve the ELD problem. The method has stronger search ability and quicker convergence speed with the ability to be used as a reliable tool for solving ELD problem. Biogeography-based optimization algorithm is used to solve the ELD problems of thermal plants [12]. Bhattacharya and Chattopadhyay proposed a hybrid technique combining differential evolution with the biogeography-based optimization algorithm in [13]. The searching ability of DE is improved by using BBO algorithm. The ELD problems are solved by using seeker optimization algorithm in [14] which exploits

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capability of human searching and understanding. In this algorithm, the search direction is mapped on empirical gradient by evaluating the response to the position changes and the step length is based on uncertainty reasoning by using a simple fuzzy rule. In [15], Chakraborty et al. presented quantum mechanics inspired particle swarm optimization which is used to solve the ELD problem. An enhanced bee swarm optimization method is proposed in [16] to solve the dynamic economic dispatch problem of thermal units considering the valve-point effects, ramp-rate limits, and the transmission power losses. To solve both complex and non-complex economic load dispatch (ELD) problems of thermal plant, a memetic algorithm, namely, aBBOmDE, is proposed in [17]. To solve the economic load dispatch problem reinforcement learning approaches is proposed in [18]. An artificial immune system based on the clonal selection principle is proposed by Basu [19] for solving dynamic economic dispatch problem. In [20] clonal selection based artificial immune system algorithm is used to solve the dynamic economic dispatch problem for generating units with valve-point effect. In [21], Nima and Hossain proposed to solve the economic dispatch problem with valve loading effect by a new modified differential evolution algorithm. The proposed MDE algorithm is inspired from genetic algorithm, particle swarm optimization and simulated annealing. An advanced parallelized particle swarm optimization algorithm with modified stochastic acceleration factors is proposed in [22] to solve large scale economic dispatch problems with prohibited operating zones, ramp-rate limits and transmission losses. In [23], Kumar et al. proposed multi-agent based hybrid particle swarm optimization technique which is applied to solve the economic load dispatch problem. This algorithm recovers the problem of PSO that is the tuning of variables, randomness and uniqueness of solution. Equal embedded algorithm has been used to solve the economic load dispatch problem with quadratic and cubic fuel cost functions and transmission losses [24]. The problems of dynamic economic dispatch are also proposed to be solved by a modified particle swarm optimization, which includes advantages of bacterial foraging and PSO [25]. Vaisakh et al. proposed a heuristic optimization methodology, namely, bacterial foraging PSO–DE algorithm which is used to solve the economic load dispatch problems [26]. The algorithm integrates bacterial foraging optimization algorithm, particle swarm optimization and differential evolution for solving non-smooth non-convex dynamic economic dispatch problem. In [27], a heuristic algorithm is presented for solving economic dispatch problems including the valve-point effect, prohibited operation zones, ramp-rate constraints and transmission losses by implementing iteration particle swarm optimization along with time varying acceleration coefficients method. In [28], a differential harmony search algorithm is proposed by combining the mechanisms of both differential evolution and harmony search to solve ELD problem. A hybrid methodology integrating bee colony optimization with sequential quadratic programming is proposed by Basu [29] for solving dynamic economic dispatch problem of generating units considering valve-point effects. In [30] an optimization methodology is proposed which is based on hybrid shuffled differential evolution algorithm which combines the benefits of shuffled frog leaping algorithm and differential evolution, to solve economic dispatch problem considering valve point loading effects. In [31] a solution for multi-objective economic dispatch problem with transmission losses is provided by semi-definite programming formulation. A new method of solving ELD problem is presented in [32] by integrating the classical gradient-based optimization technique and a new enhanced simplified swarm optimization algorithm. Abbas et al. proposed an efficient real-time approach based on optimality condition decomposition technique to solve dynamic economic dispatch problem [33]. Imperialist competitive algorithm is proposed for solving non-convex dynamic economic power dispatch problem [36]. Alsumait et al. proposed a hybrid GA–PS–SQP method to solve power system valve-point economic load dispatch problems [37]. A new approach and coding scheme is used for solving economic dispatch problems (ED) in power systems through an effortless hybrid method (EHM) [38].

This paper presents TLBO algorithm to solve ELD problem with valve point loading effect of thermal plants without considering transmission losses.

Section ‘Economic load dispatch’ describes the economic load dispatch, Section ‘Teaching learning based optimization technique’ deals with teaching learning based optimization algorithm, and section ‘Implementation of TLBO algorithm for ELD’ discusses the implementation of TLBO algorithm to ELD, Section ‘Results and discussions’, presents the simulation results and performance analysis and section ‘Conclusion’, the conclusion.

## Economic load dispatch

The primary objective of ELD involves the optimization of fuel cost. The problem is formulated as discussed below.

### *Objective functions*

The classical economic dispatch problem of finding the optimal combination of power generation which minimizes the total fuel cost while satisfying the total required demand can be mathematically stated as follows:

$$F_i(P_i) = \sum_{i=1}^{n}\left(a_iP_i^2 + b_iP_i + c_i\right) \tag{1}$$

where

$F_i(P_i)$: Total fuel cost ($/h).
$a_i, b_i, c_i$: Fuel cost coefficients of generator i.
$P_i$: The generated power of generator $i$ (MW).
$n$: Number of generators.

### *Constraints*

The optimization problem is bounded by two types of constraints

(i) Equality constraints
(ii) Inequality constraints

### *Equality constraints*

***System power balance***

$$\sum_{i=1}^{n}(P_i - P_D - P_L) = 0 \tag{2}$$

where

$P_D$: Total load (MW),
$P_L$: Transmission losses (MW).

The transmission losses can be represented as

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n}P_iB_{ij}P_j \tag{3}$$

where $B_{ij}$ transmission losses coefficient.

*Inequality constraints*

***Maximum and minimum limits of power generation***

The generation power of each generator should lie between maximum limit and minimum limit. That is

$$P_i^{\min} \leqslant P_i \leqslant P_i^{\max} \tag{4}$$

where $P_i^{\min}$ and $P_i^{\max}$ are the minimum and maximum generation of power.

*Economic load dispatch with valve point loading.* In ELD with "valve point loadings", objective function $F$ is represented by a more complex formula, given as (5). Variation of fuel cost "$F_i(P_i)$" due to valve point loading with the change of generation value is shown in Fig. 1. The objective of economic load dispatch with valve point loading is to minimize (5) subject to generator operating limit.

$$F = \min\left(\sum_{i=1}^{n} F_i(P_i)\right) = \min\left(\sum_{i=1}^{n} a_i P_i^2 + b_i P_i + c_i + \left|e_i * \sin\left\{f_i * \left(P_i^{\min} - P_i\right)\right\}\right|\right) \tag{5}$$

where $a_i$, $b_i$, $c_i$, $d_i$, $e_i$ are the cost coefficients of unit $i$.

*Economic load dispatch with valve point loading for multiple fuels.* For a power system with $n$ generators and $n_F$ fuel options for each unit, the cost function of the generator with valve-point loading is expressed as (6), where $P_{ik}^{\min}$ and $P_{ik}^{\max}$ are the minimum and maximum power generation limits of the $i$th generator with fuel option $k$, respectively; $a_{ik}$, $b_{ik}$, $c_{ik}, d_{ik}, e_{ik}$ and $f_{ik}$ are the fuel-cost coefficients of generator $i$ for fuel $k$.

$$F_i(P_i) = a_{ik} P_i^2 + b_{ik} P_i + c_{ik} + \left|e_{ik} * \sin\left\{f_{ik} * \left(P_{ik}^{\min} - P_{ik}\right)\right\}\right| \tag{6}$$

If $P_{ik}^{\min} \leqslant P_i \leqslant P_{ik}^{\max}$ for fuel option $k$; $k = 1, 2, \ldots n_F$.

## Teaching learning based optimization technique

This optimization method is based on the relationship between teacher and student in the class. It is influenced by the effect of a teacher on the output of learners in a class. It is a population based method and like other population based methods it uses a population of solutions to get the global solution. A group of learners constitute the population in TLBO. In any optimization algorithms there are numbers of different design variables. The different design variables in TLBO are represented as different subjects offered to learners and the learners' result is analogous to the "fitness", as in other population-based optimization techniques. As the teacher is considered the most learned person in the society, the best solution is analogous to teacher in TLBO. The algorithm of TLBO is divided into two parts. The first part consists of "teacher phase" and the second part consists of "learner phase". The "teacher phase" means learning from the teacher and the "learner phase" means learning through the interaction between learners in a class. Now, implementation of TLBO is described below.

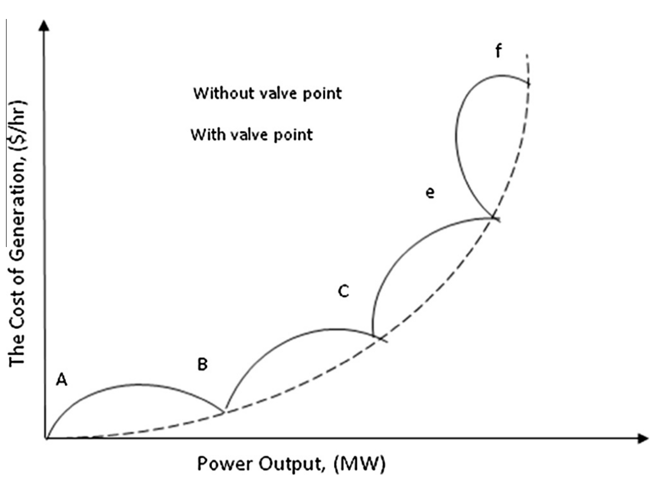



**Fig. 1.** Input–output curve with valve-point loading. a, b, c, d, e—valve points.

*Initialization*

The population $X$ is randomly initialized by a search space bounded by matrix of $N$ rows and $D$ columns.

Where

$N$ number of learners in a class *i.e.* "class size".
$D$ number of courses offered to the learners i.e. "no of designed variables".
*MAXIT* maximum number of allowable iterations.

The population $X$ is randomly initialized which is bounded by matrix of $N$ rows and $D$ columns. The $j$th parameter of the $i$th learner is assigned values randomly using the equation,

$$X_{i,j}^0 = X_j^{\min} + rand * \left(X_j^{\max} - X_j^{\min}\right) \tag{7}$$

where *rand* represents a uniformly distributed random variable within the range (0, 1), $X_j^{\min}$ and $X_j^{\max}$ represents the minimum and maximum value for $j$th parameter.

*Teacher phase*

The mean parameter of each subject of the learners in the class at generation $g$ is given as

$$M^g = \left[m_1^g, m_2^g, \ldots, m_j^g, \ldots, m_D^g\right] \tag{8}$$

The learner with minimum objective function is represented as the 'Teacher' ($X_{Teacher}$). The teacher tries to enhance the results of other individuals ($X_i$) by increasing the mean result of the classroom ($M^g$) toward his/her position $X_{Teacher}$. To obtain a new set of learners a random weighted differential vector is formed from the current mean and the desired mean parameters and added to the existing population of learners. The equation is

$$Xnew_i^g = X_i^g + rand(X_{Teacher}^g - T_F * M^g) \tag{9}$$

$T_F$ is the teaching factor. Value of $T_F$ can be either 1 or 2. The value of $T_F$ is decided randomly with equal probability as,

$$T_F = round[1 + rand(0,1)\{2 - 1\}] \tag{10}$$

where $T_F$ is not a parameter of the algorithm. Its value is randomly decided by the algorithm using above Equation. However, the algorithm is found to perform much better if the value of $T_F$ is either 1 or 2 and hence to simplify the algorithm, the teaching factor is suggested to take either 1 or 2 depending on the rounding up criteria.

If $Xnew_i^g$ is found to be better than $X_i^g$ in generation g, than it replaces on $X_i^g$ otherwise it remains $X_i^g$.

*Learner phase*

In the learner phase, the learners attempt to increase their information by interacting with others. Therefore, an individual learns new knowledge if the other individuals have more knowledge than him/her. The random interaction among the learners improves his or her knowledge. For a learner $X_i^g$, randomly select another learner $X_r^g$ as $i \neq r$. The $i$th learner of the matrix $Xnew_i^g$ is modified according the following equation.

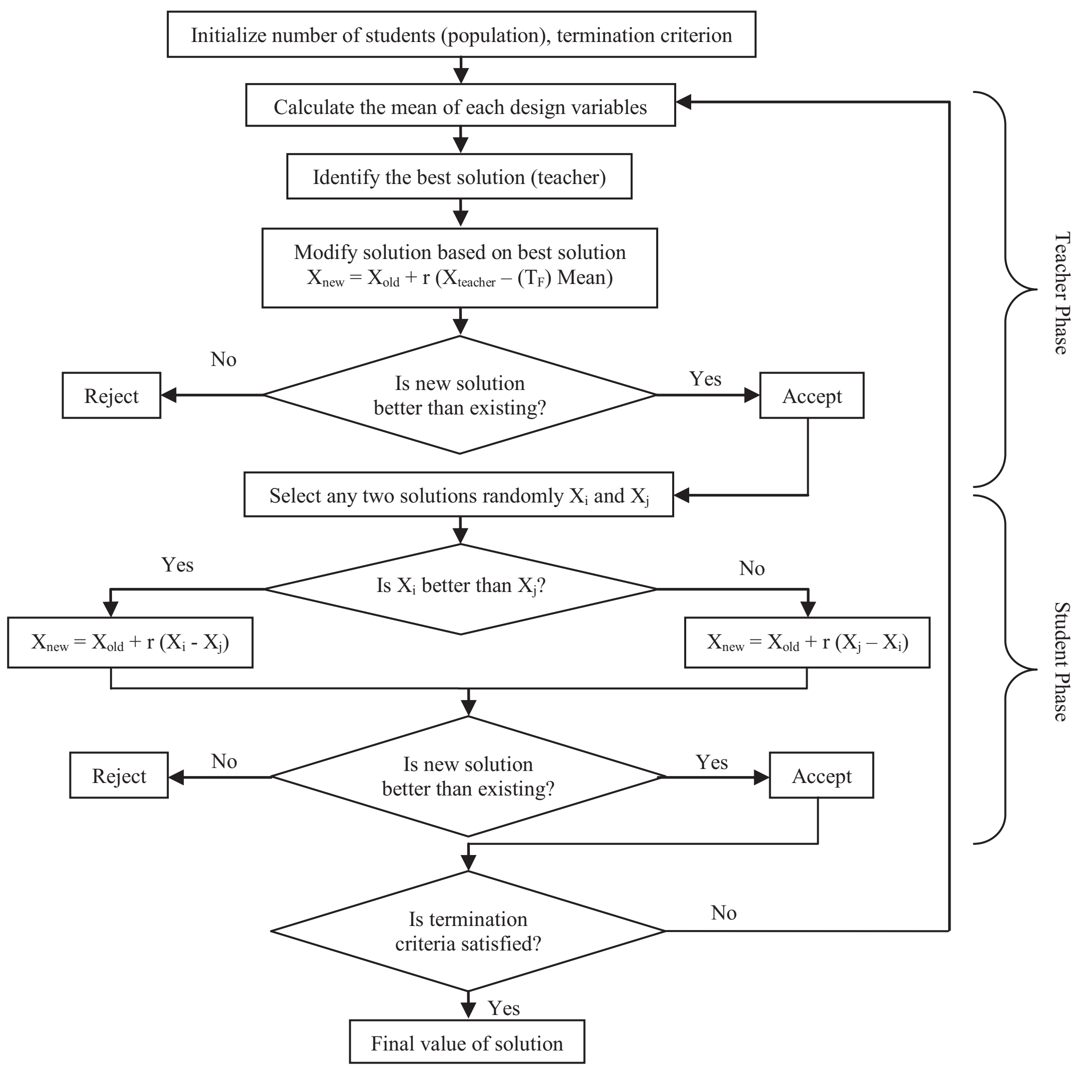
$$Xnew_i^g = X_i^g + rand * (X_i^g - X_r^g) \quad \text{if } f(X_i^g) < f(X_r^g) \tag{11}$$

$$Xnew_i^g = X_i^g + rand * (X_r^g - X_i^g) \quad \text{if } f(X_i^g) > f(X_r^g) \tag{12}$$

*Algorithm termination*

When the stopping criteria that means when MAXIT iteration is completed, then the algorithm is stop, otherwise repeat from 'Teacher Phase'.

*Flowchart of TLBO algorithm*




for solving economic load dispatch using TLBO technique are described below.

*Step 1*

Read the system data which consists of fuel cost curve coefficients of generators, power generation limits and power demand. All generators' generation is to be initialized within power generation limits. Set time count $t$ as one and repeat the following steps for the scheduled iteration.

*Step 2*

Teacher phase will start. Mean value of all generators is determined. Calculate cost value of all population size. As ELD problem

## Implementation of TLBO algorithm for ELD

The TLBO is implemented to ELD utilizing four main features. Firstly, all units are initialized within the generator limits. Then teacher phase will start. In teacher phase teacher is selected and new generator matrix is formed according to the teacher phase equation. In learner phase, again new generator matrix is to be prepared by interchanging the one generator with other. Lastly when stopping criteria is reached then algorithm is terminated. The steps

**Table 1**
Best power output for three generator system without considering transmission losses ($P_D$ = 585 MW).

| Unit power output | TLBO | Classical PSO (34) |
|---|---|---|
| $P_1$ (MW) | 268.8938 | 268.89 |
| $P_2$ (MW) | 234.2651 | 234.266 |
| $P_3$ (MW) | 81.8411 | 81.8412 |
| Total generation cost ($/h) | 5821.4 | 5821.44 |

**Table 2**
Best power output for three generator system without considering transmission losses ($P_D$ = 700 MW).

| Unit power output | TLBO | Classical PSO (34) |
|---|---|---|
| $P_1$ (MW) | 322.9408 | 322.9451 |
| $P_2$ (MW) | 277.7256 | 277.7309 |
| $P_3$ (MW) | 99.3335 | 99.3354 |
| Total generation cost ($/h) | 6838.4 | 6888.4 |

is to minimize the cost function, fittest population size corresponding minimum cost is selected as 'teacher'. Then new generator matrix is formed according to the following equation.

$$Xnew_i^g = X_i^g + rand(X_{Teacher}^g - T_F * M^g) \quad (13)$$

$Xnew_i^g$ = New generator matrix,
$X_i^g$ = Initialization generator matrix,
$X_{Teacher}^g$ = Fittest generator (teacher),
$M^g$ = Mean value of all generators.

$T_F$ is the teaching factor. Value of $T_F$ can be either 1 or 2. The value of $T_F$ is decided randomly with equal probability as,

$$T_F = round[1 + rand(0,1)\{2-1\}] \quad (14)$$

If new generator matrix $Xnew_i^g$ is found to be a superior learner than initialized generator matrix $X_i^g$ in generation g, than it replaces inferior learner $X_i^g$ in the matrix.

*Step 3*

Learner phase will start. Here generation is improved by interaction with different learners. For a learner $X_i^g$ (*i*th population size), another learner $X_r^g$ (*r*th population size) is selected. The *i*th learner of the matrix $Xnew_i^g$ is modified according the following equation.

$$\begin{aligned} Xnew_i^g &= X_i^g + rand * (X_i^g - X_r^g) \quad \text{if } f(X_i^g) < f(X_r^g) \\ Xnew_i^g &= X_i^g + rand * (X_r^g - X_i^g) \quad \text{if } f(X_i^g) > f(X_r^g) \end{aligned} \quad (15)$$

*Step 4*

If the termination criterion is satisfied, the iterative process is stopped. The termination criteria used in this work is the maximum number of iterations. The best fitness and the corresponding generation retained in the memory at the end of the algorithm is stored when termination criteria is satisfied.

**Table 3**
Best power output for three generator system without considering transmission losses ($P_D$ = 800 MW).

| Unit power output | TLBO | Classical PSO (34) |
|---|---|---|
| $P_1$ (MW) | 369.9383 | 369.9355 |
| $P_2$ (MW) | 315.5174 | 315.5187 |
| $P_3$ (MW) | 114.5443 | 114.5438 |
| Total generation cost ($/h) | 7738.5 | 7738.51 |

**Table 4**
Comparison with different methods for three generator system without considering transmission losses.

| Sl. No. | Load demand (MW) | Conventional method ($/h) (34) | GA method ($/h) (34) | TLBO method ($/h) |
|---|---|---|---|---|
| 1. | 585 | 5821.45 | 5827.5 | **5821.4** |
| 2. | 700 | 6838.41 | 6877.2 | **6838.4** |
| 3. | 800 | 7738.51 | 7756.8 | **7738.5** |

***Pseudo code of TLBO***
Set $k$ = 1
$D$ = no. of generators
$N$ = number of learners in a class i.e. population size.
$X^i_{\min}$ = Minimum value of generators.
$X^i_{\max}$ = Maximum value of generators.
Generate initial students of the classroom i.e. generation of all generators randomly.
Calculate objective function $f(X)$ for whole students of the classroom i.e. all generators.
**WHILE** (the termination conditions are not met)
$\{Teacher\ Phase\}$
Calculate the mean of each design variable $M^g$.
Identify the best solution (teacher)
**FOR** $i \to n$
Calculate teaching factor $T_F^i = round[1 + rand(0,1)\{2-1\}]$
Modify solution based on best solution (teacher)
$Xnew_i^g = X_i^g + rand(X_{Teacher}^g - T_F * M^g)$
Calculate objective function for new mapped student $f(X^i_{new})$
**IF** $X^i_{new}$ is better than $X^i$, $f(X^i_{new}) < f(X^i)$
$X^i_{new} = X^i$
Check whether $X^i_{new}$ is within limits.
**IF** $X^i_{new} > X^i_{\max}$
$X^i_{new} = X^i_{\max}$
**ELSE IF** $X^i_{new} < X^i_{\min}$
$X^i_{new} = X^i_{\min}$.
**END**
**END IF** $\{End\ of\ Teacher\ Phase\}$
$\{Learner\ Phase\}$
Randomly select another learner $X^r$, such that $i \neq r$
**IF** $X^i$ is better than $X^r$, i.e. $f(X^i) < f(X^r)$
$X^i_{new} = X^i + rand(0,1)(X^i - X^r)$
**ELSE**
$X^i_{new} = X^i + rand(0,1)(X^r - X^i)$
**END IF**
**IF** $X^i_{new}$ is better than $X^i$, $f(X^i_{new}) < f(X^i)$
$X^i_{new} = X^i$
Check whether $X^i_{new}$ is within limits.
**IF** $X^i_{new} > X^i_{\max}$
$X^i_{new} = X^i_{\max}$
**ELSE IF** $X^i_{new} < X^i_{\min}$
$X^i_{new} = X^i_{\min}$.
**END**
**END IF** $\{End\ of\ Learner\ Phase\}$
**END FOR**
Set $k = k + 1$
**END WHILE**

Post process results and visualization.

## Results and discussions

The applicability of the TLBO algorithm for practical application has been tested in three test cases. Case 1 consists of three unit systems [34], case 2 consists of thirteen unit system [35] and case 3 consists of forty unit system [35]. The programs are developed using MATLAB 7.01 and the system configuration is Pentium IV processor with 3.2 GHz speed and 1 GB RAM. Computational results are based on 30 trials.

**Table 5**
Best power output for three generator system with valve point loading without considering transmission losses ($P_D$ = 850 MW).

| Unit power output | TLBO |
|---|---|
| $P_1$ (MW) | 394.5243 |
| $P_2$ (MW) | 56.2764 |
| $P_3$ (MW) | 399.1993 |
| Total generation cost($/h) | 8280.9 |

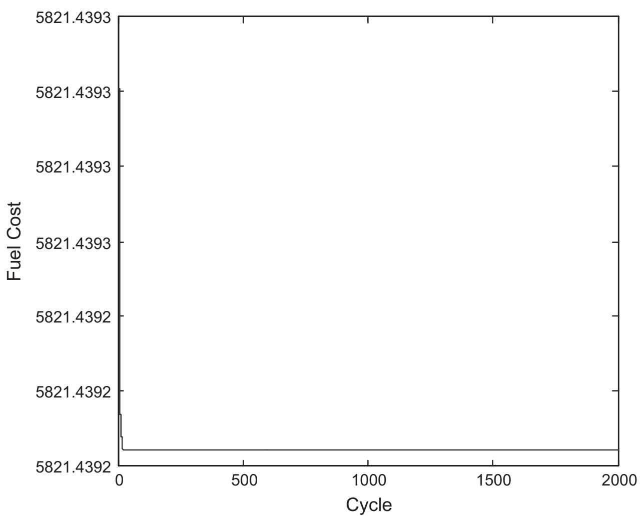



**Fig. 2.** Convergence characteristic of 3-generator system for 585 MW.

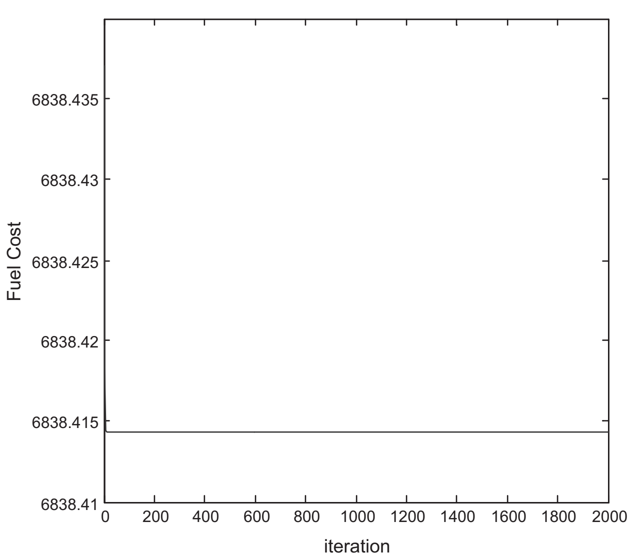



**Fig. 3.** Convergence characteristic of 3-generator system for 700 MW.

## *Setting of TLBO parameter*

Similar to other optimization techniques, parameters such as population size are to be determined before its implementation. It is to be determined that an intermediate value for the population size gives an increase in efficiency and a higher converged score for the same number of generations. Following parameters are most fit for the TLBO algorithm.

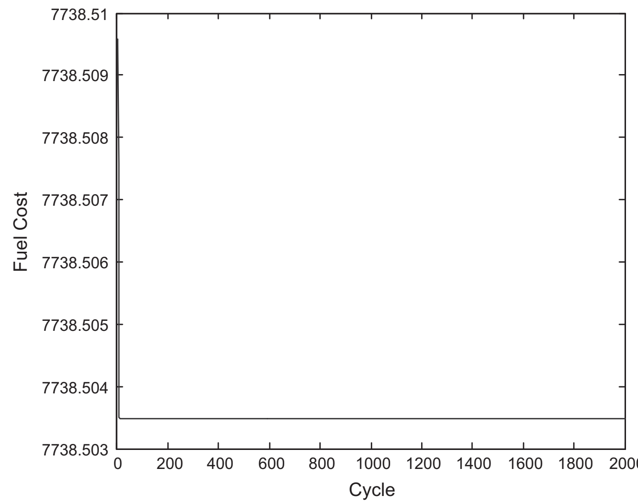



**Fig. 4.** Convergence characteristic of 3-generator system for 800 MW.

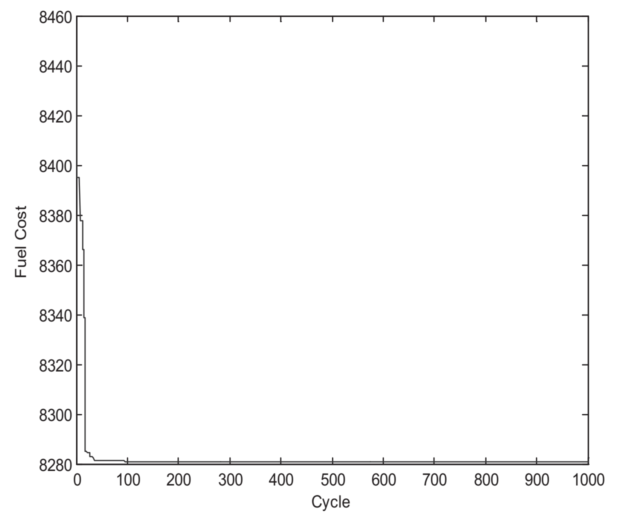



**Fig. 5.** Convergence characteristic of 3-generator system for 850 MW with considering valve point loading effect.

**Table 6**
Best power output for thirteen generator system without considering transmission losses ($P_D$ = 1800 MW).

| Unit power output | TLBO |
|---|---|
| $P_1$ (MW) | 364.9932 |
| $P_2$ (MW) | 227.9523 |
| $P_3$ (MW) | 217.4649 |
| $P_4$ (MW) | 95.2258 |
| $P_5$ (MW) | 106.6728 |
| $P_6$ (MW) | 123.5435 |
| $P_7$ (MW) | 112.5300 |
| $P_8$ (MW) | 144.2271 |
| $P_9$ (MW) | 126.0757 |
| $P_{10}$ (MW) | 60.2360 |
| $P_{11}$ (MW) | 48.4754 |
| $P_{12}$ (MW) | 91.3640 |
| $P_{13}$ (MW) | 81.2393 |
| Total generation cost($/h) | 18141.6 |

**Table 7**
Best power output for thirteen generator system with valve point loading without considering transmission losses ($P_D$ = 1800 MW).

| Unit power output | TLBO | NN-EPSO (35) |
|---|---|---|
| $P_1$ (MW) | 448.7988 | 490.0000 |
| $P_2$ (MW) | 224.6004 | 189.0000 |
| $P_3$ (MW) | 149.6106 | 214.0000 |
| $P_4$ (MW) | 109.8659 | 160.0000 |
| $P_5$ (MW) | 109.8664 | 90.0000 |
| $P_6$ (MW) | 109.8891 | 120.0000 |
| $P_7$ (MW) | 109.8607 | 103.0000 |
| $P_8$ (MW) | 109.8962 | 88.0000 |
| $P_9$ (MW) | 109.9019 | 104.0000 |
| $P_{10}$ (MW) | 77.3953 | 13.0000 |
| $P_{11}$ (MW) | 77.4043 | 58.0000 |
| $P_{12}$ (MW) | 92.4209 | 66.0000 |
| $P_{13}$ (MW) | 70.4896 | 55.0000 |
| Total generation cost ($/h) | 18,115 | 18442.59 |

**Table 8**
Best power output for thirteen generator system with valve point loading without considering transmission losses ($P_D$ = 2520 MW).

| Unit power output | TLBO | GA [35] | SA [35] | GA-SA [35] | EP-SQP [35] |
|---|---|---|---|---|---|
| $P_1$ (MW) | 623.5641 | 628.32 | 668.40 | 628.23 | 628.3136 |
| $P_2$ (MW) | 299.2522 | 356.49 | 359.78 | 299.22 | 299.0524 |
| $P_3$ (MW) | 299.2019 | 359.43 | 358.20 | 299.17 | 299.0474 |
| $P_4$ (MW) | 159.7330 | 159.73 | 104.28 | 159.12 | 159.6399 |
| $P_5$ (MW) | 159.7350 | 109.86 | 60.36 | 159.95 | 159.6560 |
| $P_6$ (MW) | 159.7242 | 159.73 | 110.64 | 158.85 | 158.4831 |
| $P_7$ (MW) | 160.3826 | 159.63 | 162.12 | 157.26 | 159.6749 |
| $P_8$ (MW) | 159.4098 | 159.73 | 163.03 | 159.93 | 159.7265 |
| $P_9$ (MW) | 159.3962 | 159.73 | 161.52 | 159.86 | 159.6653 |
| $P_{10}$ (MW) | 77.3997 | 77.31 | 117.09 | 110.78 | 114.0334 |
| $P_{11}$ (MW) | 77.4040 | 75.00 | 75.00 | 75.00 | 75.0000 |
| $P_{12}$ (MW) | 92.3988 | 60.00 | 60.00 | 60.00 | 60.0000 |
| $P_{13}$ (MW) | 92.3985 | 55.00 | 119.58 | 92.62 | 87.5884 |
| Total generation cost ($/h) | 24,197 | 24398.23 | 24970.91 | 24275.71 | 24266.44 |

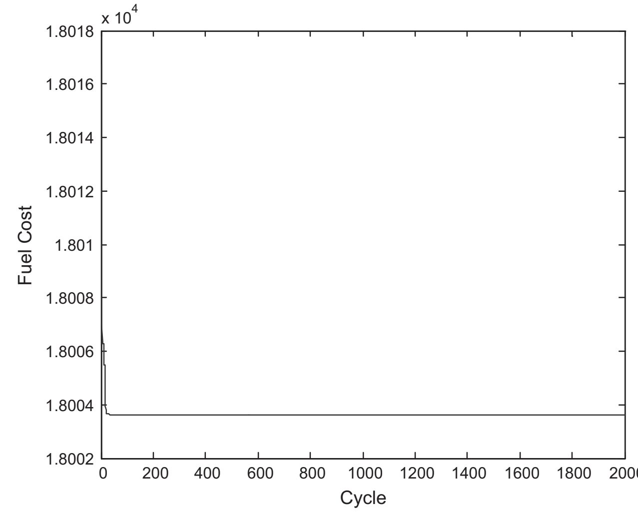



**Fig. 6.** Convergence characteristic of 13-generator system for 1800 MW.

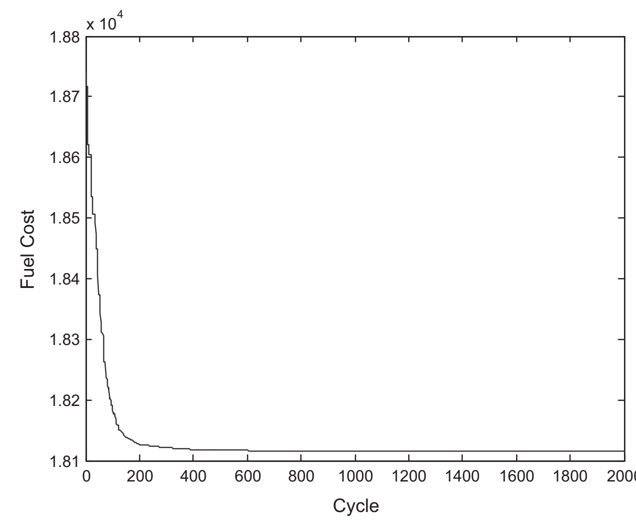



**Fig. 7.** Convergence characteristic of 13-generator system for 1800 MW by considering valve point loading effect.

*Case 1: Three unit systems*

In this case a three unit system is solved for ELD using the proposed TLBO algorithm. The generation cost coefficients and power generation limits are taken from [34]. Here transmission losses are neglected. The total production cost obtained for the three unit systems of 585 MW, 700 MW and 800 MW without losses is 5821.4 $/h, 6838.4 $/h and 7738.5 $/h respectively. The details of the power dispatch of each unit are given in Tables 1–3. Table 5 gives best power output with valve point loading without considering transmission losses for 850 MW. It can be seen that the power output of the units in each iteration satisfies the generation. Further, the sum of power generation of each unit for each iteration equals the load demand. Table 4 provides comparison of the total cost obtained using TLBO algorithm with that of other techniques for without losses. It is clearly seen that the proposed method shows better result than PSO, GA [34] while satisfying all the constraints considered. Thereby, it is clear that the new proposed algorithm is efficient and cheap (in terms of generating cost) than the other algorithms. In other words, the proposed algorithm is capable of giving a more optimum solution. Figs. 2–4 shows the graphs between number of iterations vs. cost in $/h for load of 585 MW, 700 MW and 800 MW respectively. Fig. 5 shows convergence characteristic of 3-generator system for 850 MW with considering valve point loading effect.

*Case 2: Thirteen unit system*

In this case a thirteen unit system is solved for ELD using the proposed TLBO algorithm. The generation cost coefficients and power generation limits are taken from [35]. Here transmission losses are neglected. Power generation limits and valve point loading are also included. The corresponding dispatch of units without considering transmission losses but with valve point loading is

**Table 9**
Comparison with different methods for thirteen generator system without considering transmission losses with valve point loading effect.

| Sl. No. | Load demand (MW) | GA ($/h) [35] | SA ($/h) [35] | NN-EPSO ($/h) [35] | GA-SA ($/h) [35] | EP-SQP ($/h) [35] | TLBO ($/h) |
|---|---|---|---|---|---|---|---|
| 1. | 1800 | – | – | 18442.59 | – | – | **18,115** |
| 2. | 2520 | 24398.23 | 24970.91 | – | 24275.71 | 24266.44 | **24,197** |

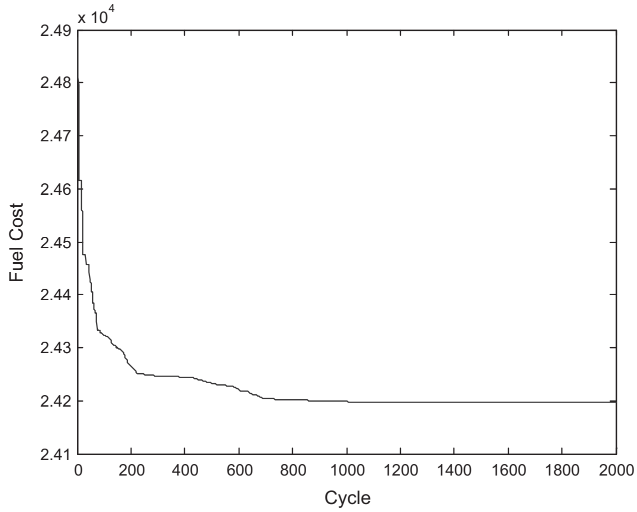



**Fig. 8.** Convergence characteristic of 13-generator system for 2520 MW by considering valve point loading effect.

**Table 10**
Best power output for forty generator system with valve point loading without considering transmission losses ($P_D$ = 10500 MW).

| Unit power output | TLBO | NN-EPSO (35) |
|---|---|---|
| $P_1$ (MW) | 36.1161 | 114.0000 |
| $P_2$ (MW) | 37.9455 | 114.0000 |
| $P_3$ (MW) | 61.8403 | 120.0000 |
| $P_4$ (MW) | 93.4369 | 190.0000 |
| $P_5$ (MW) | 83.3052 | 97.0000 |
| $P_6$ (MW) | 120.2602 | 140.0000 |
| $P_7$ (MW) | 290.4140 | 300.0000 |
| $P_8$ (MW) | 200.0000 | 300.0000 |
| $P_9$ (MW) | 293.7905 | 300.0000 |
| $P_{10}$ (MW) | 210.5287 | 300.0000 |
| $P_{11}$ (MW) | 337.4764 | 375.0000 |
| $P_{12}$ (MW) | 249.7551 | 375.0000 |
| $P_{13}$ (MW) | 380.7705 | 500.0000 |
| $P_{14}$ (MW) | 125.2402 | 500.0000 |
| $P_{15}$ (MW) | 487.4984 | 500.0000 |
| $P_{16}$ (MW) | 500.0000 | 500.0000 |
| $P_{17}$ (MW) | 319.7599 | 402.6000 |
| $P_{18}$ (MW) | 237.2392 | 225.0000 |
| $P_{19}$ (MW) | 516.5296 | 508.0000 |
| $P_{20}$ (MW) | 524.5736 | 458.0000 |
| $P_{21}$ (MW) | 540.1990 | 356.0000 |
| $P_{22}$ (MW) | 549.3921 | 394.0000 |
| $P_{23}$ (MW) | 550.0000 | 355.0000 |
| $P_{24}$ (MW) | 522.9545 | 525.0000 |
| $P_{25}$ (MW) | 532.1005 | 310.0000 |
| $P_{26}$ (MW) | 542.7990 | 448.0000 |
| $P_{27}$ (MW) | 56.7790 | 72.0000 |
| $P_{28}$ (MW) | 23.8696 | 131.0000 |
| $P_{29}$ (MW) | 12.7165 | 75.0000 |
| $P_{30}$ (MW) | 86.0264 | 67.0000 |
| $P_{31}$ (MW) | 190.0000 | 151.0000 |
| $P_{32}$ (MW) | 190.0000 | 112.0000 |
| $P_{33}$ (MW) | 190.0000 | 139.0000 |
| $P_{34}$ (MW) | 192.4549 | 90.0000 |
| $P_{35}$ (MW) | 189.1622 | 129.0000 |
| $P_{36}$ (MW) | 195.0759 | 104.0000 |
| $P_{37}$ (MW) | 109.6457 | 36.0000 |
| $P_{38}$ (MW) | 110.0000 | 89.0000 |
| $P_{39}$ (MW) | 109.3120 | 104.0000 |
| $P_{40}$ (MW) | 501.2304 | 550.0000 |
| Total generation cost ($/h) | 12,996 | 130328.325 |

shown in Table 6. The power output for each unit satisfies the generation limit constraints. Further, the sum of power generation of each unit for each iteration equals the load demand. Table 7 shows

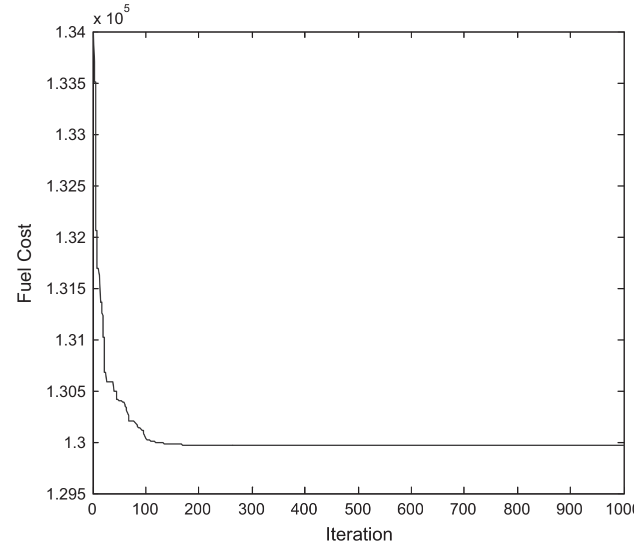



**Fig. 9.** Convergence characteristic of 40-generator system for 10,500 MW by considering valve point loading effect.

best power output with valve point loading without considering transmission losses for 1800 MW. It can be seen from Table 7 that fuel cost obtained from TLBO is less which is compared with NN-EPSO [35]. Table 8 gives best power output for 2250 MW and it is compared with GA-SA [35], EP-SQP [35]. Table 9 provides comparison of other different methods without considering transmission losses but with valve point loading effect. It can be noticed that the total cost is very much less in case of TLBO. Likewise the computation time is also less. Fig. 6 shows the graph between no. of iterations and cost in $/h for load of 1800 MW without considering transmission losses but with valve point loading effect. Figs. 7 and 8 shows convergence characteristic for 1800 and 2520 MW respectively with considering valve point loading effect.

*Case 3: Forty unit system*

In this case a forty unit system is solved for ELD using the proposed TLBO algorithm. The generation cost coefficients and power generation limits are taken from [35]. In this case transmission losses are not included and only power generation limits are included. Valve point loading effect is also included. The corresponding dispatch of units is shown in Table 10. The power output for each unit satisfies the generation limit constraints. It can be noticed that the total cost is very much less in case of TLBO. Likewise the computation time is also less. It can be seen from Table 10 that fuel cost obtained from TLBO is less compared with NN-EPSO [35]. Fig. 9 shows convergence characteristic for 10,500 MW by considering valve point loading effect without considering transmission losses.

## Conclusion

The teaching learning based optimization method has been successfully implemented to solve economic load dispatch by considering valve point loading effect. Here transmission losses and other constraints are not included. The proposed method is efficiently and effectively applied on three different test systems. The comparison of the results with other existing methods reported in the literature shows the superiority of the proposed method. Here, TLBO is able to explore the solution space for obtaining the global optimum solution. So, it can be concluded that TLBO technique is a promising method for solving ELD in power system operation.

## References


[1] Saadat Hadi. Power system analysis. New Delhi: Tata McGraw Hill Publishing Company; 2002.
[2] Basu M. Artificial bee colony optimization for multi-area economic dispatch. Electr Power Energy Syst 2013;49:181–7.
[3] Liang ZX, Glover JD. A zoom feature for a dynamic programming solution to economic dispatch including transmission losses. IEEE Trans Power Syst 1992;7(2):544–50.
[4] Lee Jia-Chu, Lin Whei-Min, Liao Gwo-Ching, Tsao Ta-Peng. Quantum genetic algorithm for dynamic economic dispatch with valve-point effects and including wind power system. Electr Power Energy Syst 2011;33:189–97.
[5] Saravuth Pothiya, Issarachai Ngamroo, Waree Kongprawechnon. Ant colony optimisation for economic dispatch problem with non-smooth cost functions. Electr Power Energy Syst 2010;32:478–87.
[6] Arul R, Ravi G, Velusami S. Chaotic self-adaptive differential harmony search algorithm based dynamic economic dispatch. Electr Power Energy Syst 2013; 50:85–96.
[7] Christober Asir Rajan C. A solution to the economic dispatch using EP based SA algorithm on large scale power system. Electr Power Energy Syst 2010;32: 583–91.
[8] Hota PK, Barisal AK, Chakrabarti R. Economic emission load dispatch through fuzzy based bacterial foraging algorithm. Electr Power Energy Syst 2010;32:794–803.
[9] Worawat Sa-ngiamvibool, Saravuth Pothiya, Issarachai Ngamroo. Multiple tabu search algorithm for economic dispatch problem considering valve-point effects. Electr Power Energy Syst 2011;33:846–54.
[10] Immanuel Selvakumar A. Enhanced cross-entropy method for dynamic economic dispatch with valve-point effects. Electr Power Energy Syst 2011; 33:783–90.
[11] Meng Ke, Wang Hong Gang, Dong ZhaoYang, Wong Kit Po. Quantum-inspired particle swarm optimization for valve-point economic load dispatch. IEEE Trans Power Syst 2010;25(1).
[12] Aniruddha Bhattacharya, Kumar Chattopadhyay Pranab. Biogeography-based optimization for different economic load dispatch problems. IEEE Trans Power Syst 2010;25(2).
[13] Aniruddha Bhattacharya, Pranab Kumar Chattopadhyay. Hybrid differential evolution with biogeography-based optimization for solution of economic load dispatch. IEEE Trans Power Syst 2010;25(4).
[14] Shaw B, Mukherjee V, Ghoshal SP. Seeker optimization algorithm: application to the solution of economic load dispatch problems. IET Gener Transm Distrib 2011;5(1):81–91.
[15] Chakraborty S, Senjyu T, Yona A, Saber AY, Funabashi T. Solving economic load dispatch problem with valve-point effects using a hybrid quantum mechanics inspired particle swarm optimization. IET Gener Transm Distrib 2011; 5(10):1042–52.
[16] Taher Niknam, Faranak Golestaneh. Enhanced bee swarm optimization algorithm for dynamic economic dispatch. IEEE Syst J 2013;7(4).
[17] Lohokare MR, Panigrahi BK, Pattnaik SS, Devi S, Mohapatra A. Neighborhood search-driven accelerated biogeography-based optimization for optimal load dispatch. IEEE Trans Syst, Man, Cybern—Part C: Appl Rev 2012;42(5).
[18] Jasmin EA, Imthias Ahamed TP, Jagathy Raj VP. Reinforcement learning approaches to economic dispatch problem. Electr Power Energy Syst 2011;33: 836–45.
[19] Basu M. Artificial immune system for dynamic economic dispatch. Electr Power Energy Syst 2011;33:131–6.
[20] Hemamalini S, Simon Sishaj P. Dynamic economic dispatch using artificial immune system for units with valve-point effect. Electr Power Energy Syst 2011;33:868–74.
[21] Nima Amjady, Hossein Sharifzadeh. Solution of non-convex economic dispatch problem considering valve loading effect by a new modified differential evolution algorithm. Electr Power Energy Syst 2010;32:893–903.
[22] Subbaraj P, Rengaraj R, Salivahanan S, Senthilkumar TR. Parallel particle swarm optimization with modified stochastic acceleration factors for solving large scale economic dispatch problem. Electri Power Energy Syst 2010;32: 1014–23.
[23] Rajesh Kumar, Devendra Sharma, Abhinav Sadu. A hybrid multi-agent based particle swarm optimization algorithm for economic power dispatch. Electr Power Energy Syst 2011;33:115–23.
[24] Chandram K, Subrahmanyam N, Sydulu M. Equal embedded algorithm for economic load dispatch problem with transmission losses. Electr Power Energy Syst 2011;33:500–7.
[25] Ahmed Yousuf Saber. Economic dispatch using particle swarm optimization with bacterial foraging effect. Electr Power Energy Syst 2012;34:38–46.
[26] Vaisakh K, Praveena P, Rao S, Mohana Rama, Kala Meah. Solving dynamic economic dispatch problem with security constraints using bacterial foraging PSO–DE algorithm. Electr Power Energy Syst 2012;39:56–67.
[27] Mohammadi-Ivatloo B, Rabiee A, Soroudi A, Ehsan M. Iteration PSO with time varying acceleration coefficients for solving non-convex economic dispatch problems. Electr Power Energy Syst 2012;42:508–16.
[28] Ling Wang, Ling-po Li. An effective differential harmony search algorithm for the solving non-convex economic load dispatch problems. Electr Power Energy Syst 2013;44:832–43.
[29] Basu M. Hybridization of bee colony optimization and sequential quadratic programming for dynamic economic dispatch. Electr Power Energy Syst 2013;44:591–6.
[30] Reddy Srinivasa A, Vaisakh K. Shuffled differential evolution for economic dispatch with valve point loading effects. Electr Power Energy Syst 2013;46:342–52.
[31] Jubril Abimbola M, Komolafe Olusola A, Alawode Kehinde O. Solving multi-objective economic dispatch problem via semidefinite programming. IEEE Trans Power Syst 2013;28(3).
[32] Azizipanah-Abarghooee Rasoul, Niknam Taher, Gharibzadeh Masihallah, Golestaneh Faranak. Robust, fast and optimal solution of practical economic dispatch by a new enhanced gradient-based simplified swarm optimization algorithm. IET Gener, Trans Distrib 2013;7(January):620–35.
[33] Abbas Rabiee, Behnam Mohammadi-Ivatloo, Mohammad Moradi-Dalvand. Fast dynamic economic power dispatch problems solution via optimality condition decomposition. IEEE Trans Power Syst 2014;29(2).
[34] Shubham Tiwari, Ankit kumar, Chaurasia GS. Economic load dispatch using particle swarm optimization. Int J Appl Innov Eng Manage 2013;2(4).
[35] Pandian S, Vijaya Muthu, Thanushkodi K. An evolutionary programming based efficient particle swarm optimization for economic dispatch problem with valve-point loading. Eur J Sci Res 2011;52(3):385–97.
[36] Behnam Mohammadi-ivatloo, Abbas Rabiee, Alireza Soroudi, Mehdi Ehsan. Imperialist competitive algorithm for solving non-convex dynamic economic power dispatch. Energy 2012;44:228–40.
[37] Alsumait JS, Sykulski JK, Al-Othman AK. A hybrid GA–PS–SQP method to solve power system valve-point economic dispatch problems. Appl Energy 2010;87: 1773–81.
[38] Pourakbari-Kasmaei M, Rashidi-Nejad M. An effortless hybrid method to solve economic load dispatch problem in power systems. Energy Convers Manage 2011;52:2854–60.