Global Journal of Pure and Applied Mathematics.
ISSN 0973-1768 Volume 13, Number 3 (2017), pp. 1049-1067

http://www.ripublication.com

# Water Evaporation algorithm to solve combined Economic and Emission dispatch problems

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## Abstract

This paper presents a new Water Evaporation Optimization (WEO) algorithm is proposed to solve an emission constrained Economic Load Dispatch (ELD) problem. The objective of the problem is to obtain the minimum production cost with lowest amount of emission. The proposed water evaporation optimization algorithm is based on the evaporation of a tiny amount of water molecules on the solid surfaces with different wettability which can be studied by molecular dynamics simulations. In order to show the proficiency of the proposed WEO algorithm it has been implemented to solve the economic load dispatch, economic emission dispatch and combined economic emission dispatch. The performance of the WEO algorithm is tested on three unit system, six unit systems and fourteen unit systems with various load demand, loss and emission coefficients. The comparison of the simulation results prove that the proposed WEO algorithm have a better performance than the existing methods.

**Keywords:** Economic dispatch, Emission dispatch, Environmental dispatch, Water evaporation optimization, Transmission losses.

## 1. INTRODUCTION

In a traditional economic load dispatch problem the objective is to minimize the production costs by an optimal allocation of load demands to the online participating generating units subject to satisfying system constraints [1]. The pollutant from the fossil fuel plant threatening the entire world and ensure that the amount of emission such as sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_x$) must be reduced. Hence it is necessary that the emission constraint must combine with economic dispatch problem and its objective is to minimize production cost with lowest emission [2-4]. The mathematical approaches like Interactive Search (IS) approach, Newton – Raphson (NR) method, Non – Linear Programming (NLP), and Quadratic Programming (QP) have been applied to solve economic emission dispatch [5-9]. The classical methods may have difficulties in finding an optimal solution due to the longest execution time and presence of non – linear & discontinuity in the problem.

As a result variety of artificial intelligence techniques such as Fuzzy Logic (FL), Evolutionary Programming (EP), Hopfield Neural Networks (HNN), Adaptive HNN, Modified Particle Swarm Optimization (MPSO), Differential Evolution (DE), Bacterial Foraging (BF), Gravitational Search (GS), opposition – based Harmony Search (HS), Artificial Bee Colony (ABC), Modified ABC, Cultural Algorithm, and quasi – oppositional based Teaching Learning Based Optimization (TLBO) were developed and applied for aforementioned problems[10-22]. Recently swarm intelligence techniques play a vital role in solving optimization problem in power system. One of the swarm intelligence technique called Flower Pollination (FP) algorithm, that is inspired by the pollination process of flowering plants have been proposed to solve combined economic and emission dispatch problems [23].

The hybrid methods also proven their ability to solve an engineering optimization problem. The combination of DE and Biogeography – based Optimization (BBO) algorithm has been developed and implemented to solve the Economic Environmental Load Dispatch problem [24]. The hybrid ant optimization system for economic emission load dispatch under fuzziness was presented [25]. The combination of PSO and gravitational search algorithm to solve EELD problem has also been discussed [26]. The hybridization of two recent meta-heuristics techniques inspired by nature, fire fly algorithm and bat algorithm has been developed to solve combined economic / environmental dispatch (CEED) problem [27].

Recently, motivated by the shallow water theory, researchers have proposed Water Evaporation Optimization (WEO) algorithm for solving global optimization problem [28]. The WEO algorithm is conceptually simple and easy to implement. The WEO algorithmic search consists of both global and local search. This guarantees that the proposed algorithm is competitive with other efficient well-known meta-heuristics. The objective of this papers it to use WEO algorithm to obtain the optimal dispatches with lowest amount of emission and compare the performances in terms of quality of solution with the recent reports.

The rest of this paper is organized as follows. EELD problem is formulated in Section "Problem Formulation". The next section "Water Evaporation Optimization" briefly describes the algorithm. The numerical simulation results and discussion is presented in the Section "Examples and Simulation Results". The final Section outlines the "Conclusion" followed by reference.

## 2. PROBLEM FORMULATION

The main objective of CEED is to minimize two inconsistent objectives such as fuel cost and emission, while satisfying operating and loading constraints. Generally the problem is formulated as follows

### 2.1. Economic dispatch

A simple smooth quadratic function of fuel cost curve of each generator is given by

$$F_i = a_i p_i^2 + b_i p_i + c_i \tag{1}$$

Where $F_i$ is the fuel cost of each generator *i* in (\$/h). $a_i$, $b_i$, $c_i$ are the cost coefficient each generator *i* in (\$/h). $p_i$ is the real power of generator *i* in MW.

Under the following constraints:

$$p_{i,\min} < p_i < p_{i,\max} \tag{2}$$

$$\sum_{i=1}^{nG} p_i = p_D + p_L \tag{3}$$

Where $P_D$ is the total demand and $P_L$ represents the active transmission losses. $P_{i,\min}$ and $P_{i,\max}$ are the minimum and maximum limits, respectively for the production of the i$^{th}$ unit.

The expression of transmission loss as a function of the generated power is given by:

$$p_L = \sum_{i=1}^{nG} \sum_{j=1}^{nG} p_i B_{ij} p_j \tag{4}$$

Where $B_{ij}$ is the constant called the losses coefficient

### 2.2. Emission dispatch

Total emission of generation $E_i$ can be

$$E_i = \alpha_i p_i^2 + \beta_i p_i + \gamma_i \tag{5}$$

$E_i$ is the function of emissions in (Kg/h) and $\alpha_i$, $\beta_i$ and $\gamma_i$ are the co-efficient of emission characteristics specific to each production unit.

### 2.3. The combined economic/environmental dispatch (CEED)

The CEED studies are designed to seek the simultaneous minimization of two functions described by the same variable objects yielding a dual objective optimization problem or bi-criteria. The primary difficulty with such an optimization problem is associated with the presence of conflicts between two features. For which, we have converted this problem into a single-objective optimization problem by introducing a price penalty factor "$h_e$", therefore, the objective function to be optimized is defined as follows:

$$Min\left\{C=\sum_{i=1}^{nG}F_i(p_i)+he\sum_{i=1}^{nG}E_i(p_i)\right\} \tag{6}$$

### 2.4. Calculating the coefficient $h_e$

The coefficient "$h_{ei}$", called price penalty factor is expressed by the following function:

$$h_{ei}=\frac{F_i(p_{i,\max})}{E_i(p_{i,\max})} \tag{7}$$

To determine the price penalty factor "$h_{ei}$" associated with a given load, the following steps must be followed

1. Calculate the ratio $F_i(P_{i;max})/E_i(P_{i;max})$ for each generator
2. Sort the factor values obtained in ascending order;
3. Add the maximum generated power of each generator ($P_{i,max}$) one by one, starting with the plant capacity with the lowest price factor corresponding to the given load. Once $\sum P_{i,\max} \geq P_D$, stop calculation;
4. At this stage, "$h_{ei}$" connected to the last unit in the summing process is the price penalty factor corresponding to the given load.

For verifying the equality constraints in equation 3, we calculated "delta" of each method as follows

$$delta=\sum_{i=1}^{nG}P_i-(P_D+P_L) \tag{8}$$

## 3. WATER EVAPORATION OPTIMIZATION

The evaporation of water is very important in biological and environmental science. The water evaporation from bulk surface such as a lake or a river is different from evaporation of water restricted on the surface of solid materials. In this WEO algorithm water molecules are considered as algorithm individuals. Solid surface or substrate with variable wettability is reflected as the search space. Decreasing the surface wettability (substrate changed from hydrophility to hydrophobicity) reforms the water aggregation from a monolayer to a sessile droplet. Such a behavior is consistent with how the layout of individuals changes to each other as the algorithm progresses. And the decreasing wettability of surface can represent the decrease of objective function for a minimizing optimization problem. Evaporation flux rate of the water molecules is considered as the most appropriate measure for updating individuals which its pattern of change is in good agreement with the local and global search ability of the algorithm and make this algorithm have well converged behavior and simple algorithmic structure. The details of the water evaporation optimization algorithm are well presented in [28].

In the WEO algorithm, each cycle of the search consists of following three steps (i) Monolayer Evaporation Phase, this phase is considered as the global search ability of the algorithm (ii) Droplet Evaporation Phase, this phase can be considered as the local search ability of the algorithm and (iii) Updating Water Molecules, the updating mechanism of individuals.

### 3.1 Monolayer Evaporation Phase

In the monolayer evaporation phase the objective function of the each individuals $Fit_i^t$ is scaled to the interval [-3.5, -0.5] and represented by the corresponding $E_{sub}(i)^t$ inserted to each individual (substrate energy vector), via the following scaling function.

$$E_{sub}(i)^t = \frac{(E_{\max} - E_{\min}) \times \left(Fit_i^t - Min(Fit)\right)}{\left(MaX(Fit) - Min(Fit)\right)} + E_{\min} \tag{9}$$

where $E_{max}$ and $E_{min}$ are the maximum and minimum values of $E_{sub}$ respectively. After generating the substrate energy vector, the Monolayer Evaporation Matrix (MEP) is constructed by the following equation.

$$MEP_{ij}^t = \begin{cases} 1 if\ rand_{ij} \leq \exp\left(E_{sub}(i)^t\right) \\ 0 if\ rand_{ij} \geq \exp\left(E_{sub}(i)^t\right) \end{cases} \tag{10}$$

Where $MEP_t^{ij}$ is the updating probability for the j<sup>th</sup> variable of the i<sup>th</sup> individual or water molecule in the t<sup>th</sup> iteration of the algorithm. In this way an individual with better objective function is more likely to remain unchanged in the search space.

### 3.2 Droplet Evaporation Phase

In the droplet evaporation phase, the evaporation flux is calculated by the following equation.

$$J(\theta) = J_o P_o \left( \frac{2}{3} + \frac{\cos^3 \theta}{3} - \cos \theta \right) (1 - \cos \theta) \tag{11}$$

where $J_o$ and $P_o$ are constant values. The evaporation flux value is depends upon the contact angle Ɵ, whenever this angle is greater and as a result will have less evaporation. The contact angle vector is represented the following scaling function.

$$\theta(i)^t = \frac{(\theta_{\max} - \theta_{\min}) \times (Fit_i^t - Min(Fit))}{(Max(Fit) - Min(Fit))} + \theta_{\min} \tag{12}$$

Where the min and max are the minimum and maximum functions. The $\Theta_{\min}$ & $\Theta_{\max}$ values are chosen between $-50^o < \Theta < -20^o$ is quite suitable for WEO. After generating contact angle vector $\Theta\ (i)^t$ the Droplet Probability Matrix (DEP) is constructed by the following equation.

$$DEP_{ij}^t = \begin{cases} 1 if\ rand_{ij} < J\left(\theta_i^{(t)}\right) \\ 0 if\ rand_{ij} \geq J\left(\theta_i^{(t)}\right) \end{cases} \tag{13}$$

Where $DEP^t_{ij}$ is the updating probability for the $j^{th}$ variable of the $i^{th}$ individual or water molecule in the $t^{th}$ iteration of the algorithm.

### 3.3 Updating Water Molecules

In the WEO algorithm the number of algorithm individuals or number of water molecules (nWM) is considered constant in all tth iterations, where t is the number of current iterations. Considering a maximum value for algorithm iterations (tmax) is essential for this algorithm to determine the evaporation phase and for stopping criterion. When a water molecule is evaporated it should be renewed. Updating or evaporation of the current water molecules is made with the aim of improving objective function. The best strategy for regenerating the evaporated water molecules is using the current set of water molecules (WM(t)). In this way a random permutation based step size can be considered for possible modification of individual as:

$$S = rand.\left(WM^{(t)}\left[permute1(i)(j)\right] - WM^{(t)}\left[permute2(i)(j)\right]\right) \tag{14}$$

Where rand is a random number in [0,1] range, permute1and permute 2 are different rows of permutation functions. i is the number of water molecule, j is the number of dimensions of the problem. The next set of molecules ($WM^{(t+1)}$) is generated by adding this random permutation based step size multiplied by the corresponding updating probability (monolayer evaporation and droplet evaporation probability) and can be stated mathematically as:

$$WM^{(t+1)} = WM^{(t)} + S \times \begin{cases} MEP^{(t)}\; t \leq t_{\max}/2 \\ DEP^{(t)}\; t > t_{\max}/2 \end{cases} \tag{15}$$

Each water molecule is compared and replaced by the corresponding renewed molecule based on objective function. It should be noted that random permutation based step size can help in two aspects. In the first phase, water molecules are more far from each other than the second phase. In this way the generated permutation based step size will guarantee global and local capability in each phase.
The WEO algorithm can be summarized as follows:

**Step 1:** Initialize all the algorithm and problem parameters, randomly initialize all water molecules.

**Step 2:** Generating water evaporation matrix
Every water molecule follow the evaporation probability rules specified for each phase of the algorithm based on the Eqs. (10) and (15). For $t \leq t_{\max}/2$, water molecules are globally evaporated based on monolayer evaporation probability MEP by using Eq (10). for $t > t_{\max}/2$, evaporation occurs based on the droplet evaporation probability DEP by using Eq (13). It should be noted that for generating monolayer and droplet evaporation probability matrices, it is necessary to generate the correspondent substrate energy vector and contact angle vector by using Eqs (9) and (12) respectively.

**Step 3:** Generating random permutation based step size matrix
A random permutation based step size matrix is generated according to Eq. (14)

**Step 4:** Generating evaporated water molecules and updating the matrix of water molecules
The evaporated set of water molecules $WM^{(t+1)}$ is generated by adding the product of step size matrix and evaporation matrix to the current set of molecules $WM^{(t)}$ by using Eq. (15). These molecules are evaluated based on the objective function. For the molecule i (i = 1,2, ....nWM) if the newly generated molecule is better than the current one, the latter should be replaced. Return the best water molecule as the output of the algorithm

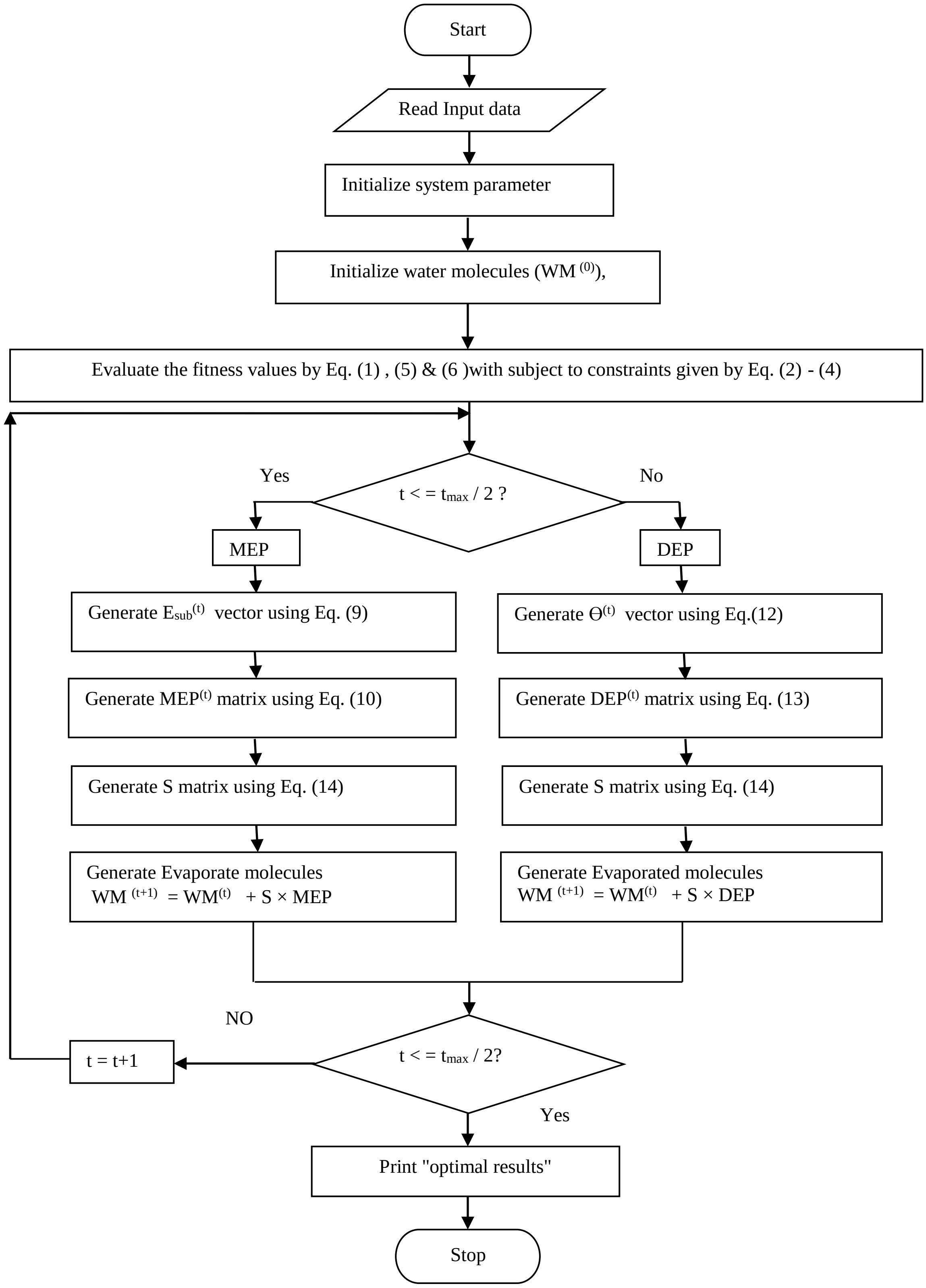

**Figure 1:** Flowchart for the proposed WEO algorithm to solve EELD

**Step 5:** Terminating condition check
If the number of iteration of the algorithm (t) becomes larger than the maximum number of iterations ($t_{max}$), the algorithm terminates. Otherwise go to step 2.
The detailed flowchart for the implementation of WEO algorithm for solving EELD problem is shown in Fig.1.

## 4. EXAMPLES AND SIMULATION RESULTS

The proposed methodology has been tested with different sample systems and the proposed algorithm is developed in Matlab environment and is implemented using Intel(R) Core(TM) i5-4200U CPU@1.60 GHz 2.30 GHz processor. The effectiveness of the proposed WEO algorithm for ELD problem has been validated by comparing the simulation results obtained from the other methods which are available in literature. The WEO algorithm parameters for all test systems are chosen as the number of water molecules (nWM) = 10, maximum number of algorithm iteration ($t_{max}$) = 100, $MEP_{min}$ = 0.03, $MEP_{max}$ = 0.6, $DEP_{min}$ = 0.6, $DEP_{max}$ = 1.

### 4.1 Test System 1

The proposed WEO algorithm is applied to CEED problem consisting of 3 generating units. The each generating unit cost coefficients, power generation limits, emission coefficients have been presented in the literature [27]. In this test system four different load demands 400MW, 500MW, 600MW and 700MW are considered with losses. The results obtained by the proposed WEO algorithm in comparison with existing techniques FA, BA, HYB and GA is presented in table 1. The results shows that proposed and existing algorithms meet the demand and satisfying system constraints. From the comparison it is clear that the proposed algorithm achieve the minimized cost with lowest amount of emission with least loss for all load demands.
The convergence characteristic of proposed algorithm for test system 1 is shown in figure 2. The converged results ensure that objective value is minimized from maximum value to minimum for the load demands of 400 MW, 500 MW, 600 MW and 700 MW imply that the proposed WEO algorithm outperforms the existing methods.

### 4.2 Test System 2

In order to test the performance of the WEO algorithm, the sample system considered with 6 generating units with transmission loss, emission with a load demands of 700MW, 800MW, 900MW & 1000MW. The generating unit's data are taken from [27]. In order to show the superiority of the proposed WEO algorithm, it has been implemented to obtain economic dispatch to minimize the cost, environment dispatch to minimize emission and combined economic emission dispatch to minimize both cost as well as emission.

**Table 1:** Optimal dispatches obtained by the proposed WEO algorithm for test system 1

| Power demand (MW) | Methods | $P_1$(MW) | $P_2$ (MW) | $P_3$ (MW) | Pl (MW) | Emission (kg/h) | Total cost ($/h) | he ($/kg) |
|---|---|---|---|---|---|---|---|---|
| 400 | FA [27] | 102.5405 | 153.7319 | 151.1396 | 7.4124 | 200.22 | 29559.79 | 43.5598 |
| | BA[27] | 102.5444 | 153.7331 | 151.1345 | 7.4124 | 200.22 | 29559.79 | |
| | HYB[27] | 102.5404 | 153.7362 | 151.1354 | 7.4124 | 200.22 | 29559.79 | |
| | GA[27] | 102.617 | 153.825 | 151.011 | 7.4132 | 200.26 | 29563 | |
| | **WEO** | **101.9867** | **154.0796** | **150.9487** | **7.0100** | **199.90** | **29527.02** | |
| | | | | | | | | |
| 500 | FA [27] | 128.8249 | 192.5856 | 190.2825 | 11.6936 | 311.15 | 39209.93 | 44.0792 |
| | BA[27] | 128.8280 | 192.5792 | 190.2858 | 11.6936 | 311.15 | 39209.94 | |
| | HYB[27] | 128.8343 | 192.5670 | 190.2918 | 11.6936 | 311.15 | 39209.96 | |
| | GA[27] | 128.997 | 192.683 | 190.11 | 11.6964 | 311.27 | 39220 | |
| | **WEO** | **129.0091** | **199.9959** | **189.9927** | **11.0000** | **310.27** | **39140.79** | |
| | | | | | | | | |
| 600 | FA [27] | 155.4508 | 231.7974 | 229.7533 | 17.0022 | 461.22 | 50937.31 | 44.5985 |
| | BA[27] | 155.4504 | 231.7980 | 229.7531 | 17.0022 | 461.22 | 50937.31 | |
| | HYB[27] | 155.4422 | 231.8029 | 229.7565 | 17.0022 | 461.22 | 50937.29 | |
| | GA[27] | 155.714 | 231.895 | 229.479 | 17.0039 | 461.35 | 50948 | |
| | **WEO** | **155.3678** | **231.9138** | **229.6872** | **16.9703** | **461.17** | **50933.24** | |
| | | | | | | | | |
| 700 | FA [27] | 182.5988 | 271.2809 | 269.4859 | 23.3664 | 651.57 | 64861.51 | 45.1179 |
| | BA[27] | 182.6030 | 271.2805 | 269.4821 | 23.3663 | 651.57 | 64861.52 | |
| | HYB[27] | 182.6015 | 271.2801 | 269.4839 | 23.3663 | 651.57 | 64861.52 | |
| | GA[27] | 182.783 | 271.478 | 269.132 | 23.365 | 651.63 | 64866 | |
| | **WEO** | **182.6276** | **271.2676** | **269.3678** | **23.2607** | **651.37** | **64847.78** | |

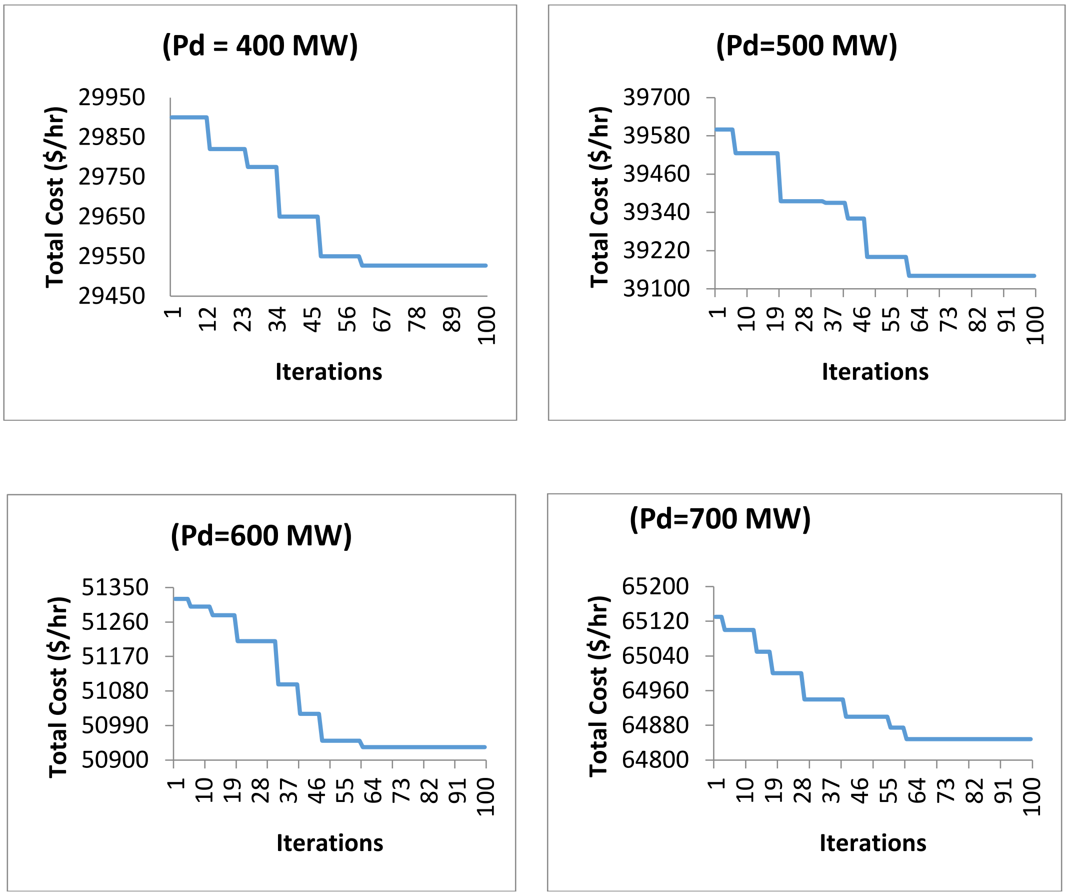

**Figure.2.** Convergence characteristics of test system 1

### *4.2.1 Economic Load Dispatch*

In an Economic Load Dispatch (ELD) problem the objective is to minimize the total fuel cost subject to satisfying system constraints without considering the emission and loss. An optimal economic dispatch obtained by the proposed as well as existing algorithms for the load demands of 700 MW, 800MW, 900MW, and 1000MW is presented in Table 2. From the results it is clear that the proposed algorithm achieve the least cost then the FA, BA, and HYB algorithms for all load demands and all the algorithms are satisfying system constraints completely. The objective values versus iterations are depicted in figure 3. The converged results indicate that the proposed algorithm is highly competitive with recent techniques.

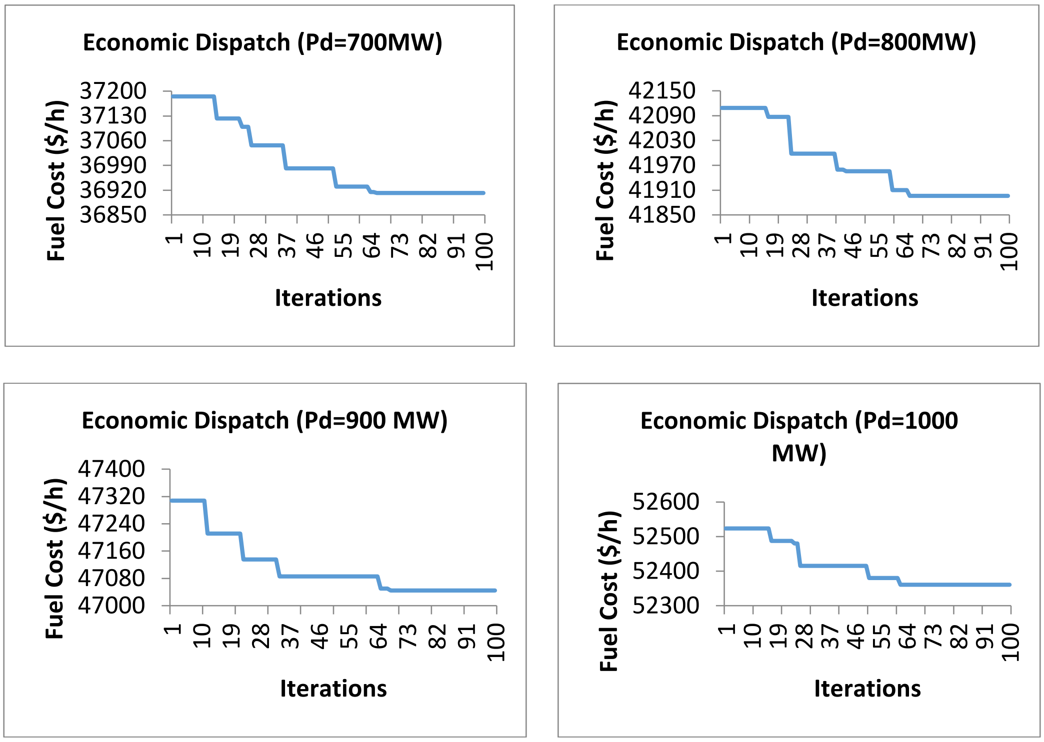

**Figure.3.** Objective values versus iterations of test system 2 for ELD

**Table 2:** Economic dispatch results obtained by the WEO, FA, BA, and HYB algorithms for test system 2

| Power demand (MW) | Method | P1 (MW) | P2 (MW) | P3 (MW) | P4 (MW) | P5 (MW) | P6 (MW) | Pl (MW) | Cost ($/h) | Emission (kg/h) | Delta (MW) | T (s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 700 | FA | 28.3151 | 10.0000 | 118.8216 | 118.8329 | 230.9801 | 212.4811 | 19.43 | 36912.19 | 501.02 | 0.000256 | 62.76 |
| | BA | 28.2862 | 10.0000 | 118.9333 | 118.6760 | 230.7614 | 212.7731 | 19.43 | 36912.08 | 501.02 | 0.002465 | 10.75 |
| | HYB | 28.2491 | 10.0000 | 118.8833 | 118.5778 | 230.5090 | 213.2178 | 19.43 | 36912.19 | 501.08 | 0.000298 | 42.8158 |
| | **WEO** | **28.2561** | **10.0000** | **118.9011** | **118.8124** | **230.6188** | **212.8354** | **19.42** | **36911.81** | **500.98** | **0.000264** | **15.86** |
| | | | | | | | | | | | | |
| 800 | FA | 32.5802 | 14.4799 | 141.5531 | 136.0259 | 257.6647 | 243.0274 | 25.33 | 41896.69 | 649.00 | 0.000259 | 62.11 |
| | BA | 32.5881 | 14.4837 | 141.5522 | 136.0414 | 257.6644 | 242.9983 | 25.33 | 41896.57 | 648.98 | 0.002533 | 10.96 |
| | HYB | 32.5948 | 14.4813 | 141.5422 | 136.0417 | 257.6676 | 243.0029 | 25.33 | 41896.69 | 648.98 | 0.000254 | 41.97 |
| | **WEO** | **32.5876** | **14.4816** | **141.5393** | **136.0325** | **257.6618** | **243.0136** | **25.32** | **41896.00** | **648.97** | **0.000256** | **16.13** |
| | | | | | | | | | | | | |
| 900 | FA | 36.8533 | 21.0808 | 163.9323 | 153.2154 | 284.1733 | 272.7325 | 31.98 | 47045.24 | 821.97 | 0.000255 | 62.11 |
| | BA | 36.8451 | 21.0798 | 163.9281 | 153.2228 | 284.1814 | 272.7331 | 31.98 | 47045.12 | 821.98 | 0.002607 | 10.99 |
| | HYB | 36.8477 | 21.0751 | 163.9349 | 153.2317 | 284.1583 | 272.7401 | 31.98 | 47045.24 | 821.98 | 0.000255 | 42.05 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **WEO** | **36.8462** | **21.0800** | **163.9313** | **153.2237** | **284.1682** | **272.7312** | **31.98** | **47044.89** | **821.96** | **0.000255** | **16.21** |
| | | | | | | | | | | | | |
| 1000 | FA | 41.1577 | 27.7856 | 186.5641 | 170.5797 | 310.8197 | 302.5749 | 39.48 | 52361.25 | 1022.48 | 0.000279 | 61.95 |
| | BA | 41.1683 | 27.7835 | 186.95 | 170.5787 | 310.8257 | 302.5530 | 39.48 | 52361.12 | 1022.46 | 0.002684 | 11.10 |
| | HYB | 41.1657 | 27.7818 | 186.5718 | 170.5838 | 310.8128 | 302.5654 | 39.48 | 52361.25 | 1022.47 | 0.000267 | 41.95 |
| | **WEO** | **41.1668** | **27.7822** | **186.5714** | **170.5813** | **310.8195** | **302.5542** | **39.48** | **52360.96** | **1022.45** | **0.000272** | **16.27** |

### *4.2.2 Economic Environmental Dispatch (EED)*

In an EED problem the objective is to minimize the emission with satisfying system constraints despite of fuel cost and loss. An optimal EED obtained by the proposed as well as existing algorithms for all load demands with fulfilling constraints are presented in Table 3. The EED results ensure that the proposed WEO algorithm obtains the minimized emission of $NO_x$ for all the four load demands then the existing algorithms reported in the literature. The emission convergence characteristics are plotted in the figure 4. The converged result indicates that the proposed WEO algorithm is capable of producing better outcome then other algorithms.

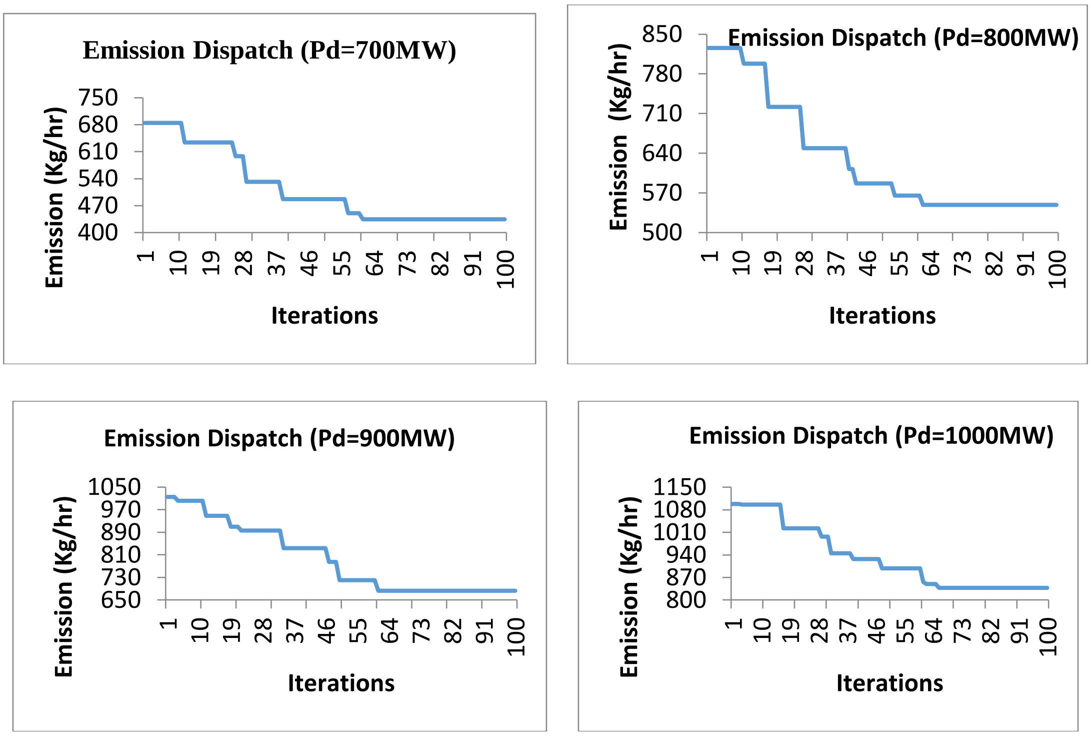

**Figure.4.** Objective values versus iterations of test system 2 for EED

**Table 3:** Comparison of economic environmental dispatch results for test system 2

| Power demand (MW) | Method | P1 (MW) | P2 (MW) | P3 (MW) | P4 (MW) | P5 (MW) | P6 (MW) | Pl (MW) | Cost ($/h) | Emission (kg/h) | Delta (MW) | T(s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 700 | FA | 80.1523 | 82.4019 | 113.9655 | 113.4758 | 163.4493 | 163.0944 | 16.53 | 38101.09 | 434.13 | 0.000536 | 41.99 |
| | BA | 80.1431 | 82.4033 | 113.9684 | 113.4763 | 163.4530 | 163.0950 | 16.53 | 38100.95 | 434.13 | 0.000515 | 13.24 |
| | HYB | 80.1506 | 82.4054 | 113.9570 | 113.4851 | 163.4436 | 163.0975 | 16.53 | 38101.13 | 434.13 | 0.000541 | 11.16 |
| | **WEO** | **80.1439** | **82.4043** | **113.9657** | **113.4772** | **163.4471** | **163.0951** | **16.53** | **38100.72** | **434.12** | **0.000538** | **10.98** |
| | | | | | | | | | | | | |
| 800 | FA | 100.5399 | 103.7475 | 127.0118 | 126.3499 | 182.1959 | 181.7376 | 21.58 | 43719.20 | 548.70 | 0.000631 | 43.53 |
| | BA | 100.5295 | 103.7579 | 127.0076 | 126.3466 | 182.2088 | 181.7321 | 21.58 | 43719.15 | 548.70 | 0.000610 | 14.18 |
| | HYB | 100.5207 | 103.7662 | 127.0024 | 126.3547 | 182.1999 | 181.7385 | 21.58 | 43719.14 | 548.70 | 0.000638 | 11.80 |
| | **WEO** | **100.5211** | **103.7511** | **127.0032** | **126.3518** | **182.2081** | **181.7382** | **21.57** | **43718.39** | **548.69** | **0.000624** | **11.21** |
| | | | | | | | | | | | | |
| 900 | FA | 120.9389 | 125.3301 | 140.1958 | 139.3394 | 201.0812 | 200.4822 | 27.36 | 49650.29 | 682.62 | 0.000724 | 41.90 |
| | BA | 120.9330 | 125.3313 | 140.1994 | 139.3392 | 201.0855 | 200.4791 | 27.36 | 49650.14 | 682.62 | 0.000713 | 13.36 |
| | HYB | 120.9357 | 125.3202 | 140.1992 | 139.3479 | 201.0706 | 200.4940 | 27.36 | 49649.97 | 682.62 | 0.000703 | 11.12 |
| | **WEO** | **120.9362** | **125.3211** | **140.1993** | **139.3393** | **201.0808** | **200.4812** | **27.36** | **49649.53** | **682.61** | **0.000708** | **10.26** |
| | | | | | | | | | | | | |
| 1000 | FA | 125.0000 | 150.0000 | 156.2191 | 155.2644 | 224.0618 | 223.1839 | 33.73 | 55456.64 | 837.77 | 0.000890 | 44.31 |
| | BA | 125.0000 | 150.0000 | 156.2704 | 155.1559 | 224.0577 | 223.2458 | 33.73 | 55456.49 | 837.77 | 0.000835 | 14.14 |
| | HYB | 125.0000 | 150.0000 | 156.0719 | 155.2412 | 224.2263 | 223.1934 | 33.73 | 55456.24 | 837.77 | 0.000832 | 11.65 |
| | **WEO** | **125.0000** | **150.0000** | **156.0792** | **155.2183** | **224.2173** | **223.2163** | **33.73** | **55456.12** | **837.76** | **0.000833** | **10.87** |

### *4.2.3 Combined Economic Environmental Dispatch (CEED)*

In the CEED problem the objective is to minimize the total fuel cost with small amount of emission subject to meet all system constraints. The table 4 shows the simulation results of CEED problem got by the WEO, FA, BA and HYB algorithms. The results demonstrate that all algorithms are clearly satisfies the load demands and power generation limits. The result also implies that the proposed WEO algorithm alone got the minimum fuel cost with least emission then the earlier techniques for all load demands. The objective value versus iterations graph shows in figure 5 imply that the cost is minimized from larger value and it will guarantee that the proposed algorithm is capable of obtaining competitive results then existing algorithms.

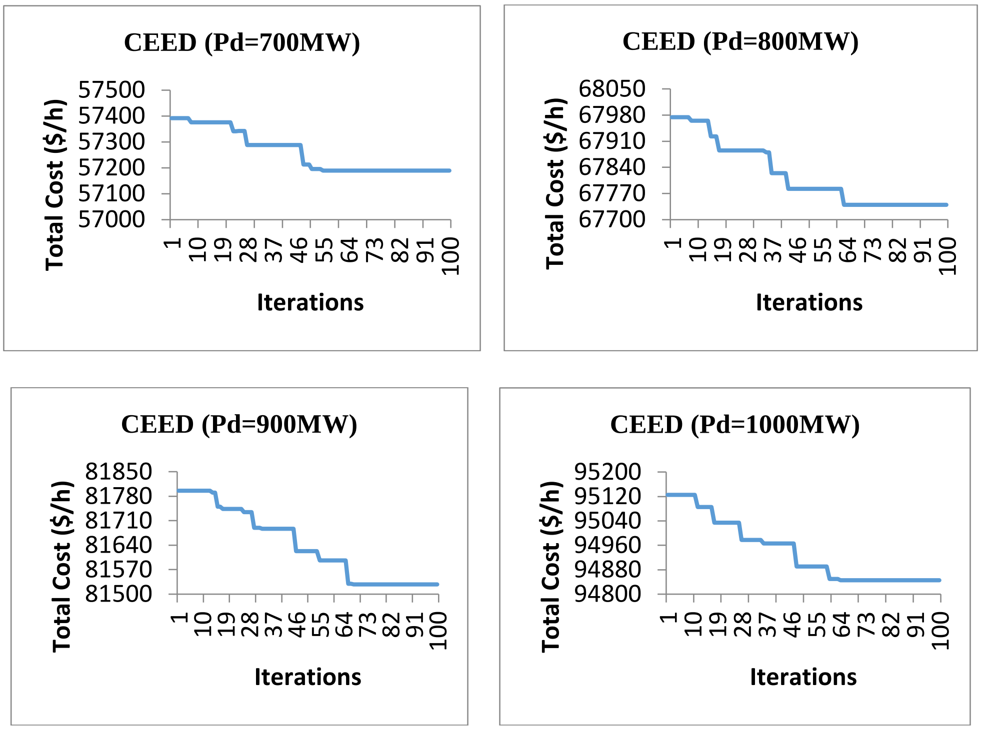

**Figure.5.** Objective values versus iterations of test system 2 for CEED

**Table 4:** Comparison of CEED result for test system 2

| Power demand (MW) | Method | P1 (MW) | P2 (MW) | P3 (MW) | P4 (MW) | P5 (MW) | P6 (MW) | Pl (MW) | Cost ($/h) | Emission (kg/h) | Total cost ($/h) | $h_e$ ($/kg) | Delta (MW) | T(s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 700 | FA | 62.1127 | 61.6689 | 119.9746 | 119.4606 | 178.1913 | 175.6480 | 17.05 | 37500.93 | 439.61 | 57190.01 | 44.7880 | 0.000504 | 43.03 |
| | BA | 62.1032 | 61.6698 | 119.9712 | 119.4756 | 178.1929 | 175.6432 | 17.05 | 37500.84 | 439.61 | 57190.01 | 44.7880 | 0.000499 | 13.47 |
| | HYB | 62.0815 | 61.6634 | 119.9733 | 119.4775 | 178.2088 | 175.6518 | 17.05 | 37500.48 | 439.62 | 57190.01 | 44.7880 | 0.000518 | 11.63 |
| | **WEO** | **62.0893** | **61.6638** | **119.9716** | **119.4758** | **178.1915** | **175.6549** | **17.05** | **37500.17** | **439.60** | **57189.11** | **44.7880** | **0.000512** | **11.54** |
| | | | | | | | | | | | | | | |
| 800 | FA | 76.5733 | 79.2629 | 135.2268 | 134.1554 | 199.7071 | 197.2628 | 22.18 | 42784.41 | 557.20 | 67740.26 | 44.7880 | 0.000551 | 42.49 |
| | BA | 76.5756 | 79.2678 | 135.2250 | 134.1530 | 199.7107 | 197.2560 | 22.18 | 42784.52 | 557.20 | 67740.26 | 44.7880 | 0.000555 | 13.52 |
| | HYB | 76.5704 | 79.2611 | 135.2379 | 134.1536 | 199.7035 | 197.2616 | 22.18 | 42784.36 | 557.20 | 67740.26 | 44.7880 | 0.000564 | 11.28 |
| | **WEO** | **76.5712** | **79.2635** | **135.2372** | **134.1532** | **199.7063** | **197.2528** | **22.18** | **42784.22** | **557.19** | **67739.85** | **44.7880** | **0.000558** | **11.21** |
| | | | | | | | | | | | | | | |
| 900 | FA | 92.3321 | 98.3848 | 150.1937 | 148.5649 | 220.3986 | 218.1350 | 28.00 | 48350.59 | 693.79 | 81529.09 | 47.8222 | 0.000643 | 42.78 |
| | BA | 92.3288 | 98.3982 | 150.1948 | 148.5588 | 220.4025 | 218.1256 | 28.00 | 48350.77 | 693.78 | 81529.09 | 47.8222 | 0.000636 | 13.59 |
| | HYB | 92.3216 | 98.3928 | 150.1928 | 148.5709 | 220.4065 | 218.1242 | 28.00 | 48350.54 | 693.79 | 81529.09 | 47.8222 | 0.000647 | 11.66 |
| | **WEO** | **92.3218** | **98.3892** | **150.1931** | **148.5639** | **220.4028** | **218.1249** | **28.00** | **48349.85** | **693.77** | **81527.48** | **47.8222** | **0.000642** | **11.52** |
| | | | | | | | | | | | | | | |
| 1000 | FA | 107.1685 | 116.5498 | 165.6550 | 163.4014 | 242.0380 | 239.7979 | 34.61 | 54124.28 | 851.53 | 94846.36 | 47.8222 | 0.000698 | 42.03 |
| | BA | 107.1631 | 116.5483 | 165.6599 | 163.4001 | 242.0355 | 239.8036 | 34.61 | 54124.12 | 851.53 | 94846.36 | 47.8222 | 0.000702 | 13.41 |
| | HYB | 107.1613 | 116.5507 | 165.6535 | 163.4032 | 242.0460 | 239.7958 | 34.61 | 54124.13 | 851.53 | 94846.36 | 47.8222 | 0.000702 | 11.22 |
| | **WEO** | **107.1622** | **116.5485** | **165.6537** | **163.4009** | **242.0415** | **239.7982** | **34.61** | **54123.83** | **851.52** | **94845.59** | **47.8222** | **0.000701** | **11.08** |

### 4.3 Test System 3

To examine the superior quality of solution and robustness of the proposed WEO algorithm, a fourteen unit system is considered. The data for this system is provided in [27]. In this test system the losses are included. The load demands are 1750 MW, 2150 MW and 2650 MW. The results obtained by the proposed WEO as well as existing algorithms are given in the Table 5. The results ensure that the WEO algorithm reach the minimized fuel cost with least emission then FA, BA and HYB algorithms for all three load demands subject to satisfying all system constraints. The cost convergence characteristics curves are depicted in figure 6. The converged results indicate that the proposed algorithm is highly competitive with recent techniques.

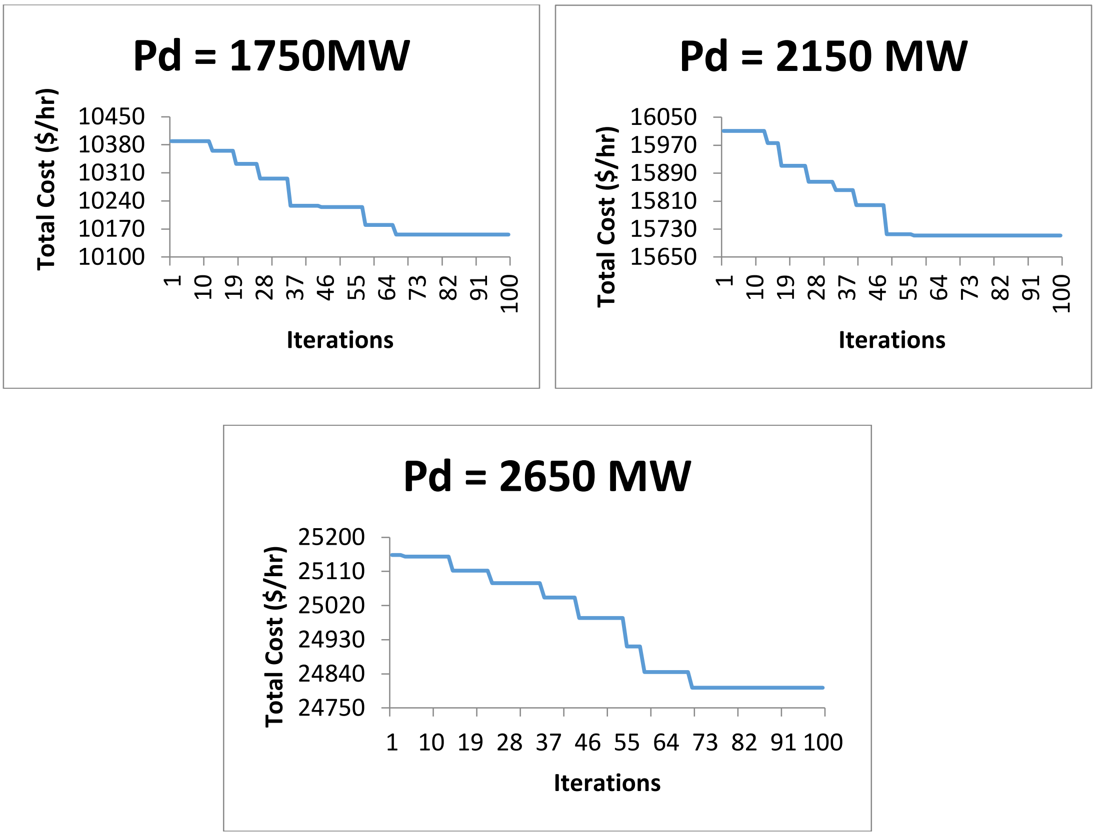

**Figure.6.** Objective values versus iterations of test system 3 for CEED

**Table 5:** Results obtained by different method for CEED of test system 3

| **Power Demand (MW)** | **1750** | | | | **2150** | | | | **2650** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Method** | FA | BA | HYB | **WEO** | FA | BA | HYB | **WEO** | FA | BA | HYB | **WEO** |
| **P1(MW)** | 182.0588 | 178.9878 | 181.2480 | **181.6548** | 257.4562 | 268.9503 | 256.5416 | **258.2461** | 346.3009 | 359.8860 | 351.3142 | **353.9869** |
| **P2(MW)** | 150 | 150 | 150 | **150** | 150.1828 | 150.0210 | 150.5956 | **150.2635** | 200.4597 | 195.0677 | 194.3160 | **194.9861** |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **P3(MW)** | 129.9967 | 130 | 130 | **130** | 130 | 130 | 130 | **130** | 130 | 130 | 130 | **130** |
| **P4(MW)** | 130 | 130 | 130 | **130** | 130 | 130 | 130 | **130** | 130 | 130 | 130 | **130** |
| **P5(MW)** | 150.0011 | 150 | 150 | **150** | 202.0693 | 203.5662 | 199.3316 | **199.9572** | 269.2312 | 287.4177 | 273.6004 | **269.4086** |
| **P6(MW)** | 169.9179 | 172.9990 | 171.2620 | **172.2532** | 302.0464 | 283.4375 | 305.0391 | **299.9954** | 456.8215 | 457.1745 | 452.0668 | **454.1241** |
| **P7(MW)** | 139.9398 | 143.3521 | 141.1432 | **140.2274** | 215.2976 | 219.1369 | 221.2425 | **216.2547** | 308.0642 | 286.2891 | 310.2679 | **309.2143** |
| **P8(MW)** | 118.1137 | 119.1891 | 120.6329 | **120.0022** | 182.3827 | 184.7476 | 176.0317 | **184.6588** | 242.7468 | 237.2652 | 242.1170 | **241.4005** |
| **P9(MW)** | 150.0109 | 143.6663 | 144.0593 | **143.0013** | 160 | 160 | 160 | **160** | 160 | 160 | 160 | **160** |
| **P10(MW)** | 160 | 160 | 160 | **160** | 160 | 160 | 160 | **160** | 160 | 160 | 160 | **160** |
| **P11(MW)** | 78.6056 | 80 | 80 | **80** | 80 | 80 | 80 | **80** | 80 | 80 | 80 | **80** |
| **P12(MW)** | 80 | 80 | 80 | **80** | 80 | 80 | 80 | **80** | 80 | 80 | 80 | **80** |
| **P13(MW)** | 55 | 85 | 85 | **85** | 85 | 85 | 85 | **85** | 85 | 85 | 85 | **85** |
| **P14(MW)** | 54.9997 | 55 | 55 | **55** | 55 | 55 | 55 | **55** | 55 | 55 | 55 | **55** |
| **Pl(MW)** | 28.6506 | 28.2001 | 28.3502 | **27.1402** | 39.4420 | 39.8682 | 38.7895 | **38.38** | 53.6343 | 53.1115 | 53.6926 | **53.12** |
| **Cost($/h)** | 7821.83 | 7830.04 | 7826.33 | **7820.63** | 10029.79 | 10000.49 | 10035.15 | **10024.07** | 13322.13 | 13279.53 | 13318.16 | **13316.85** |
| **Emission(Kg/h)** | 1925.67 | 1916.46 | 1919.17 | **1916.27** | 3725.97 | 3753.39 | 3722.33 | **3717.69** | 7309.84 | 1355.98 | 7312.32 | **7309.22** |
| **Total Cost($/h)** | 10168.99 | 10165.97 | 10165.56 | **10156.37** | 15730.32 | 15742.98 | 15730.12 | **15711.26** | 24809.94 | 24839.84 | 24809.86 | **24803.30** |
| **$h_e$($/Kg)** | 1.2189 | 1.2189 | 1.2189 | **1.2189** | 1.5299 | 1.5299 | 1.5299 | **1.5299** | 1.5715 | 1.5715 | 1.5715 | **1.5715** |
| **Delta (MW)** | 0.006455 | 0.004576 | 0.004718 | **0.004668** | 0.006908 | 0.007355 | 0.007355 | **0.007352** | 0.009929 | 0.011338 | 0.010408 | **0.010976** |
| **T(s)** | 458.29 | 60.13 | 209.81 | **75.21** | 428.11 | 55.47 | 157.97 | **58.68** | 460.46 | 56.40 | 130.48 | **68.29** |

## 5. CONCLUSION

The minimization of emissions like carbon dioxide ($CO_2$), sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_X$) from fossil – fueled electric power plants has received significant attention in recent years because these emissions can creates an atmospheric pollution. Hence it is necessary to include environmental emissions in a traditional economic load dispatch problem. Here the objective is to minimize the fuel cost with least emission. In this paper a new Water Evaporation Optimization (WEO) algorithm has been applied successfully to solve an ELD, EED and CEED problems. The feasibility of the proposed WEO algorithm is demonstrated on three different test systems and the simulation results are compared with GA, FA, BA, and HYB algorithms. The comparison of the results shows that the proposed algorithm outperforms the existing algorithms in terms of achieving minimized fuel cost with small amount of emission.

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