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Economic/Emission Dispatch with Cogenerating Systems Using Enhanced Nature Inspired Algorithm

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ABSTRACT: The Combined Heat and Power Dispatch (CHPD) is an important optimization task in power system operation for allocating generation and heat outputs to the committed units. Teaching Learning Based Optimization (TLBO) is a recently developed heuristic algorithm based on the natural phenomenon of teaching-learning process. In order to improve the exploration and exploitation capacities of basic TLBO, Enhanced Teaching Learning Based Optimization (ETLBO) is proposed. This work aims to explore the performance and practical applicability of ETLBO on CHPD problems. The effectiveness of the proposed method is validated by carrying out extensive tests on two different CHPD problems such as economic dispatch and environmental-economic dispatch. Valve –point effects along with network loss are considered. To compare the performances of the ETLBO, statistical measures like best, mean, worst, standard deviation, epsilon, iter and sol-iter over 50 independent runs are taken. The simulation experiments reveal that ETLBO performs better in terms of solution quality and consistency. It is also found that the obtained results are satisfying the system and operational constraints that confirm the optimality.

KEYWORDS: Cogeneration systems; Enhanced teaching learning based optimization; Valve-point effects; Emission;

I. INTRODUCTION

Nowadays the energy conservation has been globally highlighted due to an expected sharp increase in energy demands and resultant increased pollution. Also the conversion of electric energy into heat energy needs efficient process because most of the energy is wasted during conversion process. In order to improve the efficiency of the existing system, cogeneration is introduced which refers to the simultaneous production of electric and heat energy from a single source. Cogeneration minimizes the energy loss during aforesaid conversion process and can significantly reduce a facility's energy use by decreasing the amount of fuel to meet the facility's electrical and thermal base loads. This reduction in energy use can produce a number of benefits, including energy cost savings; reducing gas emissions, and other environmental impacts, especially when renewable fuel sources are used.

The solution methods can be categorized into two groups: mathematical and heuristic. The mathematical approaches were applied to solve CHPD problem [1] but they require approximations in the modeling of the cost curves and are not practical as the actual cost curves are highly non-linear, non-monotonic and sometimes contain discontinuities. The heuristic search techniques such as Genetic Algorithm (GA) and its modified versions [2-4] including Genetic Algorithm based Penalty Function (GA-PF) , Improved Genetic Algorithm (IGA), Self Adaptive Real Coded Genetic Algorithm (SARGA) and Non-dominated Sorting Genetic Algorithm-II (NSGA) [5], Improved Ant Colony Search [6], Economic Dispatch with Harmony Search (EDHS) [7], Particle Swarm Optimization (PSO) [8],Time varying Acceleration Coefficients Particle Swarm Optimization (TVAC-PSO) [9] , Selective Particle Swarm Optimization (SPSO) [10], Enhanced Firefly Algorithm (EFA) [11], Self Adaptive Learning Charged System Search (SALCSSA) [12], Multi-objective line up competition algorithm [13], Improved Group Search Optimization (IGSO) [14] and a hybrid harmony – genetic approach [15] were applied to solve CHPD problem. These techniques provide

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the feasible solution but the feasible operating region of cogenerator is not well explored and in some cases test system contains erroneous data [16].

Recently, Rao et al. [17] developed a natural inspiring optimization algorithm, the so called Teaching–Learning Based Optimization (TLBO), which mimics teaching–learning process in a class between the teacher and the students. This algorithm has no user-defined parameter that makes it superior than earlier ones. In order to improve its search capability, the number of teachers, adaptive teaching factor, tutorial training and self motivated learning are introduced [18]. In this work, as a maiden attempt, the Enhanced TLBO (ETLBO) is proposed for solving CHPD problems and is tested on different scale of test systems. Comparing the numerical results with the earlier reports, ETLBO emerges out to be a stout optimization technique for solving both linear and nonlinear models of CHPD problems.

II. PROBLEM FORMULATION

The main issues, is to minimise the cost and emission subjected to system and operational constraints The CHP system's total fuel cost (1) can be mathematically represented in the following form.

$$Min\ F_T = \sum_{i=1}^{Np} F_p(P_i) + \sum_{j=1}^{Nc} F_c(P_{cj}, H_{cj}) + \sum_{k=1}^{Nh} F_h(H_k) + \left[\sum_{i=1}^{Np} E_p(P_i) + \sum_{j=1}^{Nc} E_c(P_{cj}, H_{cj}) + \sum_{k=1}^{Nh} E_h(H_k) \right] \ (\$/h) \qquad (1)$$

i.e. (1) is expanded as follows

$$F_T = \left[\begin{array}{c} \underbrace{\sum_{i=1}^{Np} a_i + b_i P_i + c_i P_i^2 + d_i P_i^3 + \left| e_i \sin(f_i (P_i^{\min} - P_i)) \right|}_{Power\ only\ units} + \\ \underbrace{\sum_{j=1}^{Nc} \alpha_j + \beta_j P_{cj} + \gamma_j P_{cj}^2 + \varepsilon_j H_{cj} + \eta_j H_{cj}^2 + \phi_j P_{cj} H_{cj}}_{Cogeneration\ units} + \\ \underbrace{\sum_{k=1}^{Nh} \varphi_k + \lambda_k H_k + \mu_k H_k^2}_{Heat\ only\ units} \end{array} \right] + \left[\begin{array}{c} \underbrace{\sum_{i=1}^{Np} \left[\omega_i + \sigma_i P_i + \psi_i P_i^2 + \tau_i e^{(\theta_i P_i)} \right]}_{Power\ only\ units} + \\ \underbrace{\sum_{j=1}^{Nc} \xi_j P_{cj}}_{Cogeneration\ units} + \\ \underbrace{\sum_{k=1}^{Nh} \vartheta_k H_k}_{Heat\ only\ units} \end{array} \right] \qquad (2)$$

The system and operating constraints are as follows:

(i) Power demand
In order to gratify the forecasted system power load requirement, the sum of all the power generating units must be equal to the system load and loss

$$\sum_{i=1}^{Np} P_i + \sum_{j=1}^{Nc} P_{cj} = P_d + P_L \qquad (MW) \qquad (3)$$

(ii) Active power loss
B-coefficients method is used to find transmission line loss and is given by,

$$P_L = \sum_{i=1}^{(Np+Nc)} \sum_{j=1}^{(Np+Nc)} P_i B_{ij} P_j \qquad (MW) \qquad (4)$$

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(iii) Heat demand

The sum of heat generated by all units at any time must be equal to heat demand and is given by

$$\sum_{j=1}^{Nc} H_{cj} + \sum_{k=1}^{Nh} H_k = H_d \qquad \text{(MWth)} \tag{5}$$

(iv) System limits

The power only unit, cogeneration unit and heat only unit operating unit is given by

$$P_i^{\min} \le P_i \le P_i^{\max} \qquad i = 1, \ldots\ldots, Np \tag{6}$$

$$P_{cj}^{\min}(H_{cj}) \le P_{cj} \le P_{cj}^{\max}(H_{cj}) \qquad j = 1, \ldots\ldots, Nc \tag{7}$$

$$H_{cj}^{\min}(P_{cj}) \le H_{cj} \le H_{cj}^{\max}(P_{cj}) \qquad j = 1, \ldots\ldots, Nc \tag{8}$$

$$H_k^{\min} \le H_k \le H_k^{\max} \qquad i = 1, \ldots\ldots, Np \tag{9}$$

III. ENHANCED TEACHING LEARNING BASED OPTIMIZATION (ETLBO)

3.1. Number of Teachers

The basic TLBO algorithm is enhanced by introducing more than one teacher to the learner (X). Thus the entire class is split into different groups of learners and individual teacher is assigned to individual group of learners.

3.2. Adaptive teaching factor

The teaching factor (T_f) is generated adaptively instead heuristic step to enhance the solution quality.

$$T_{f_i} = \frac{M_{D,i}}{M\_new_{D,i}} \qquad D=1, 2, \ldots\ldots, D_n \quad i=1, 2, \ldots\ldots, N_G \tag{10}$$

Where, D_n is the number of design variable; N_G is the number of generations, $M_{D,i}$ is the mean of the learners in any subject at iteration i and $M\_new_{D,i}$ is the position of the teacher for the same subject in iteration i.

3.3. Learning through tutorial

The knowledge acquired by learner during the tutorial hours (X') is as,

$$X'_{new,i} = (X_{old,i} + \text{Difference\_Mean}_i) + r\,(X_{hh} - X_k), \text{ if } f(X)_{hh} > f(X)_k \text{ ,Where } hh \ne k \tag{11}$$

$$X'_{new,i} = (X_{old,i} + \text{Difference\_Mean}_i) + r\,(X_k - X_{hh}), \text{ if } f(X)_k > f(X)_{hh} \text{ ,Where } hh \ne k \tag{12}$$

3.4. Self-motivated learning

The knowledge of the learner improved through self-learning process (X'') is as,

$$X''_{new,i} = X'_{new,i} + r\,(X'_{i,j} - X'_{i,p}) + r\,(X\text{teacher} - E_F\, X'_{i,j}), \text{ If } f(X'_i) < f(X'_p) \tag{13}$$

$$X''_{new,i} = X'_{new,i} + r\,(X'_{i.p} - X'_{i,j}) + r\,(X\text{teacher} - E_F\, X'_{i,j}), \text{ If } f(X'_p) < f(X'_i) \tag{14}$$

Where E_F = exploration factor = round $(1 + r)$

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IV. ETLBO IMPLEMENTATION FOR CHPD PROBLEM

3.5. Algorithmic steps of ETLBO for CHPD

Step 1: Read the problem statement and initialize algorithmic parameters:

Step 2: The design variables are generated randomly within the limits for the population size (*PS*).

$$P_{k,i}^{PU} = P_{k,\min}^{PU} + \left(P_{k,\max}^{PU} - P_{k,\min}^{PU}\right) \times r(0,1) \qquad k \in N_{PU} \tag{20}$$

$$P_{k,i}^{CHP} = P_{k,\min}^{CHP} + \left(P_{k,\max}^{CHP} - P_{k,\min}^{CHP}\right) \times r(0,1) \qquad k \in N_{CHP} \tag{21}$$

$$H_{k,i}^{CHP} = H_{k,\min}^{CHP} + \left(H_{k,\max}^{CHP} - H_{k,\min}^{CHP}\right) \times r(0,1) \qquad k \in N_{CHP} \tag{22}$$

$$H_{k,i}^{HU} = P_{k,\min}^{HU} + \left(P_{k,\max}^{HU} - P_{k,\min}^{HU}\right) \times r(0,1) \qquad k \in N_{HU} \tag{23}$$

An individual in the population consists (N_{PU}+2N_{CHP}+N_{HU}) variables, is represented in (24) and fitness is calculated for each individual.

$$PS_i = \left[P_{1,i}^{PU},..,P_{N_{PU},i}^{PU},P_{1,i}^{CHP},...,P_{N_{CHP},i}^{CHP},H_{1,i}^{CHP},..,H_{N_{CHP},i}^{CHP},H_{1,i}^{HU},..,H_{N_{HU},i}^{HU}\right] \tag{24}$$

Step 3: An individual having the minimum fitness (i.e $f\,(PH)_{\min}$) is mimicked as the chief teacher for that cycle. Assign him/her to first rank.

$$(PH_{\text{teacher}})_1 = f\,(PH)_1 \text{ where } f\,(PH)_1 = f\,(PH)_{\min} \tag{25}$$

Step 4: Select the other teachers (*T*) based on the chief teacher and rank them in the ascending order of $f\,(PH)$ value.

$$f\,(PH)_s = f\,(PH)_1 - r\,f\,(PH)_1, \text{ where s = 2, 3, ..., n.} \tag{26}$$

$$PH_s\text{,teacher} = f(PH)_s\text{ , where s = 2, 3, ..., n.} \tag{27}$$

Step 5: Assign the learners to the teachers according to their fitness value as,

$$\text{If } f\,(PH)_s \le f\,(PH)_1 < f\,(PH)_{s+1}, \text{ s = 1, 2, ...,} T\text{-1, L = 1, 2, ...}P_n \tag{28}$$

Assign the learner $f\,(PH)_1$ to teacher 's', else assign him/her to teacher 's + 1'.

Step 6: Calculate the mean result of each learners group for each subject

$$M\_new_{s,j} = PH_{s,j}, \text{ s = 1, 2, ..., } T\text{, j = 1, 2, ...,}j_n \tag{29}$$

Step 7: Evaluate the difference between the current mean and the corresponding result of the teacher of that group for each subject by utilizing the adaptive (given by Eq. 15) as:

$$\text{Difference\_Mean}_{s,j} = r\,(M\_new_{s,j} - T_f M_{s,j}) \quad \text{s = 1,2, ..., T, j = 1, 2, ..., } j_n \tag{30}$$

Step 8: Updates the learner knowledge through the tutorial hours using the Eq 16 – 17.

Step 9: Updates the learner knowledge by self learning, using the Eq 18 – 19.

Step 10: Combine all groups.

Step 11: Termination Criterion.

Repeat the procedure from step 3 to 10 until the maximum number of iteration is reached.

V. VERIFICATION VIA TEST SYSTEMS

This section details the performance of ETLBO in solving various types of CHPD problems. The ETLBO is implemented on the standard test systems comprise of 4 unit and 7 units. The program is coded in MATLAB-7.9 language and is executed on 2.3 GHz Intel core i3 personal computer with 4 GB RAM. The obtained simulation results are compared with the recent reports in term of solution quality.

Test system 1: Combined Heat and Power Dispatch with Cogenerating Sources

Guo et al. (1996) proposed this system, consists two cogeneration units and each power and heat-only unit [1]. The operational characteristics of power and heat-only units are expressed as linear function and second-order function is adopted for cogenerator. The economic dispatch is carried out for the power demand of 200 MW and head demand of 115MWth.

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The obtained optimal dispatches by the ETLBO are presented in the Table 1. The total cost attained by the ETLBO for the abovementioned demands is $ 9257.07.Comparing in terms of minimum fuel cost with the earlier reports, the ETLBO has close agreement with other methods except EDHS and SPSO. These two methods cannot be directly compared because their solutions are infeasible. Referring the FOR of CHP unit 2, the minimum real power generation is 40 MW but EDHS attains no real power generation which make the operating point to fall out of FOR hence the infeasible solution. SPSO provides a real power mismatch of -0.4 MW, this leads to less fuel cost.

Table 1 CHP dispatch results for 4-unit test system and comparison with other algorithms (P_d=200MW and H_d= 115MWth)

Methods	**Real Power Output (MW)**			**Heat Output (MWth)**			**P_d (MW)**	**H_d (MWth)**	**Cost ($/h)**
	P_1	**P_2**	**P_3**	**H_2**	**H_3**	**H_4**			
IACS [6]	0.08	150.93	49	48.84	65.79	0.37	200.1	115	9452.2
GA-PF [2]	0	159.23	40.77	39.94	75.06	0	200	115	9267.28
PSO [8]	0.05	159.43	40.57	39.97	75.03	0	200.05	115	9265.1
IGA [3]	0	160	40	39.99	75	0	200	114.99	9257.09
CPSO [9]	0	160	40	40	75	0	200	115	9257.08
SARGA [4]	0	159.99	40.01	39.99	75	0	200	114.99	9257.07
TVAC-PSO [9]	0	160	40	40	75	0	200	115	9257.07
EDHS [7]	0	200	0	0	115	0	200	115	8606.07*
SPSO [10]	0	159.7065	39.9097	40	75	0	199.616	115	9248.17*
TLBO	0	160	40	40	75	0	200	115	9257.07
ETLBO	**0**	**160**	**40**	**40**	**75**	**0**	**200**	**115**	**9257.07**

* Not feasible

Test system 2: CHPED with Environmental Aspects

This test system consists of four power-only units, two cogeneration units and a heat-only unit and data is available in the literature [5]. The power and heat demands of the system are 600MW and 150MWth respectively. The valve-

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Table 2 Economic dispatch, emission dispatch & combined economic emission dispatch results and comparison with existing methods for 7-unit test system (P_d=600MW and H_d= 150MWth)

Methods	Economic Dispatch			Emission Dispatch			Economic Emission Dispatch			
	RCGA [5]	TLBO	ETLBO	RCGA [5]	TLBO	ETLBO	SPEA 2 [5]	NSGA-II [5]	TLBO	ETLBO
P_1 (MW)	74.5357	58.0531	**52.8074**	73.3318	46.7184	**47.2117**	73.3149	73.5896	70.1193	**68.7669**
P_2	99.3518	99.4642	**98.5398**	81.0489	63.1956	**60.5702**	117.7996	106.8761	109.4694	**98.4445**
P_3	174.7196	113.0021	**112.6735**	93.4210	65.9416	**65.9821**	117.7996	119.0311	92.6683	**98.5285**
P_4	211.0170	209.0098	**209.8158**	125.2112	77.2703	**79.3252**	151.6436	163.5563	98.9833	**109.8509**
P_5	100.9363	88.0111	**93.8115**	214.9958	243.8793	**244.4299**	195.1355	188.4166	196.4287	**192.0000**
P_6	44.1036	40.0000	**40.0000**	125.7907	110.8047	**110.2**	54.0988	58.4850	40.0000	**40.0000**
H_5 (MWth)	24.3678	63.5207	**29.3704**	104.7715	17.4715	**14.40**	25.8784	26.8054	1.0457	**5.6924**
H_6	72.5270	75.0000	**75.0000**	31.9272	131.5995	**135.6**	75.5331	73.9970	75.0000	**75.0000**
H_7	53.1052	11.47922	**29.3704**	13.3013	0.9290	**0**	48.5884	49.1976	73.9543	**69.3076**
P_{loss} (MW)	NR	7.6600	**7.6499**	NR	7.8048	**7.7100**	NR	NR	7.6690	**7.5840**
Cost ($/h)	10712.86	10195.91	**10111.24**	17749.31	17302.16	**17290.26**	13448.95	13433.19	12641.14	**12402.90**
Emission (kg/h)	39.5749	28.5063	**28.1812**	16.9208	8.1522	**8.1088**	25.7810	25.8262	17.5615	**17.4093**
CPU time (s)	20.3438	5.2801	**5.2618**	22.7813	5.2801	**5.2618**	53.4688	9.7188	5.2801	**5.2618**

NR-Not Reported

point effect, emission and transmission line loss are included in the generator model that further increases the complexity of the problem. The proposed ETLBO algorithm is applied for the following operations:

Case 1: Economic (CHPED) operation Case 2: Emission (CHPEmD) operation

Case 3: Economic - emission (CHPEED) operation

In the first two formulations, the total cost and total emissions are minimized respectively subject to various constraints and weighted sum method is adopted for the third formulation in which, both objectives are equally weighted and are minimized.

Table 2 shows that the ETLBO method obtains lower fuel cost and emission level compared to TLBO, SPEA 2 [5] and NSGA-II [5] methods. Best compromise solution i.e. the solution set for which both emission and fuel cost minimizes simultaneously to a suitable level is shown in Table 2. Fig. **1** shows the pareto-optimal of ETLBO. It should be noted that, to obtain the pareto-optimal solutions, the simulation needs to run multiple times by varying the weight between 0 and 1. The overall cost of compromised solution in ETLBO is better for both convex and non-convex CHPEED problems; it only indicates its ability to reach global minimum in a consistent manner. So it may be noted that ETLBO method has a stronger ability to find the high quality solution and its convergence characteristic is also superior in both single and multi-objective optimization problems.

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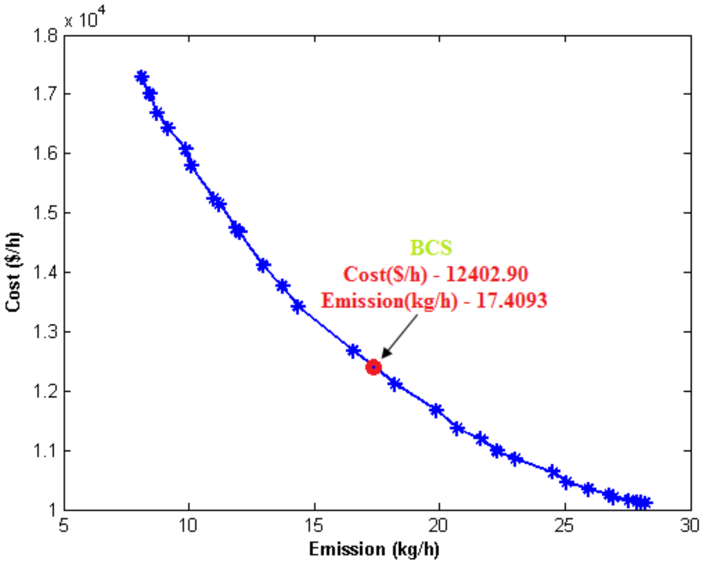

Fig. 1. Best Compromise Solution (BCS) obtained from Pareto-optimal front for 7 unit test system by ETLBO

Comparative study

Computational efficiency

The convergence characteristic of the algorithm for all test systems are presented in Fig. 2 that clears ETLBO attains the optimum solution as quick as within 100 iterations. The numerical results comparisons indicate that the ETLBO attains the optimal solution as it has good computational and search mechanism. It is also important to note that the algorithm finds the optimal solution even for large scale systems and dynamic dispatch problems.

Robustness

The performance of any heuristic search based-optimization algorithm is judged through repetitive trail runs so as to compare the strength of the algorithm. Many trials therefore are required to find out the optimum results. Again CHPED, CHPEED, RCCHPDED are real time problems, so it is desirable that each run of the program should reach close to optimum solution. Fig. 3 clearly indicates excellent success rate of the ETLBO algorithm which signifies robustness and superiority of the algorithm compared to other existing approaches.

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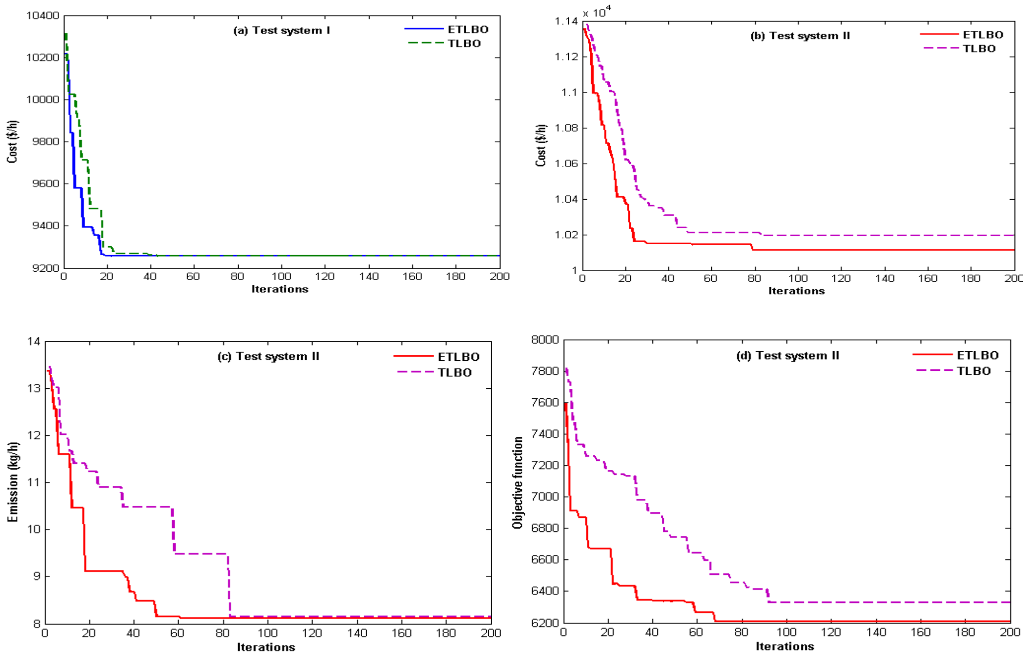

Fig. 2. Convergence characteristic of test systems (a) 4 unit (b) 7 unit – Case 1 (c) 7 unit- Case 2 (d) 7 unit- Case 3

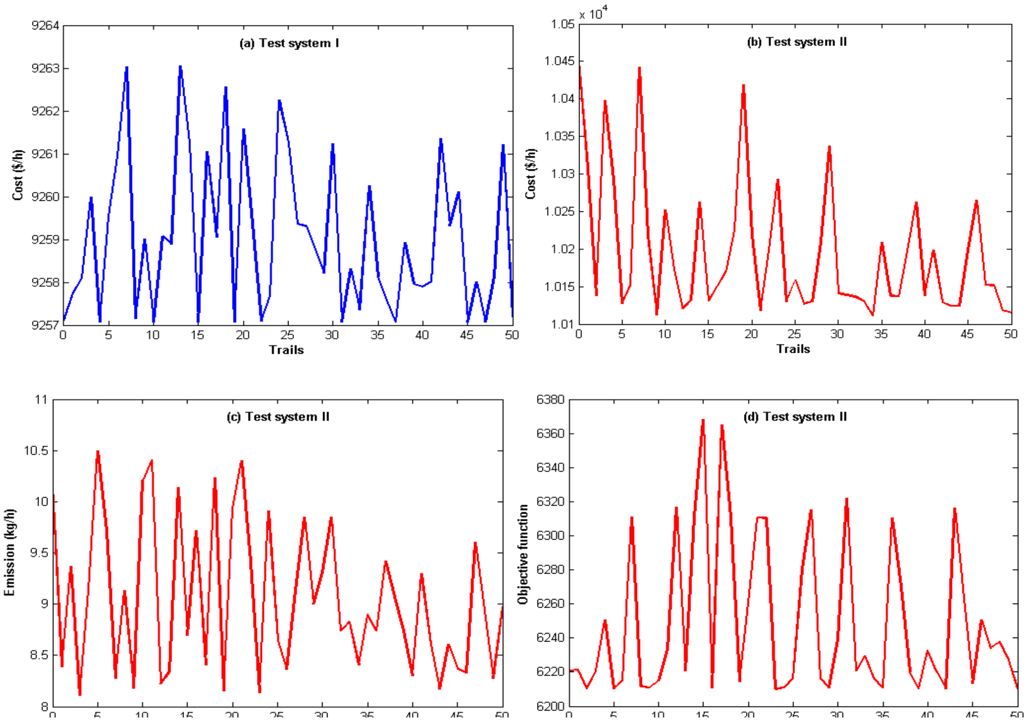

Fig. 3. Robustness characteristics (a) 4-unit (b) 7-unit Economic operation (c) 7-unit Minimum emission operation (d) 7- unit Economic emission operation

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VI. CONCLUSION

In this paper an enhanced version of the teaching learning algorithm is proposed for the solution of mixed power source dispatch involving power, cogenerating systems and heat sources. Two test systems have been implemented to illustrate the applicability of the proposed Enhanced Teaching Learning Based Optimization (ETLBO) in solving the mixed power source dispatch problems. Nonlinear characteristics of generators such as valve point loadings are considered for practical generator operation. This approach considers network loss and emission into account to make dispatch more practical and meaningful. Thus the presented approach is a good tool for the power industry to aid curbing pollution and hostile environment, which are harmful for the welfare of the society. A compromise solution has also been obtained between the cost and emission by using a Pareto optimal graph. Further the results obtained substantiate the applicability of the proposed method for solving dynamic economic dispatch with non-smooth functions. Numerical testing and a comparative analysis show that the proposed algorithm, in all test cases, outperforms other approaches reported in the literature, in that it provides a higher quality solutions and a good computational efficiency. Further study can be extended with the use of renewable energy sources.

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