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Multi-objective Economic Emission Load Dispatch using Grey Wolf Optimization

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Abstract—*This paper presents grey wolf optimization method for solving multi-objective economic emission load dispatch (EELD) problem in diverse test power systems. Grey Wolf Optimization (GWO) is a new meta-heuristic motivated from grey wolf. Diverse emission gases considered for the case studies are SOx, NOx and COx. GWO is applied on diverse test cases for finding EELD solution. Comparison of the obtained results is carried out with other techniques stated in literature which shows that GWO is effective to solve EELD.*

Keywords— Economic emission load dispatch, GWO, penalty factor, fuel cost, emission.

I. INTRODUCTION

The chief goal of EELD is to get optimum output of thermal generators in power system subjected to several constraints to diminish the operating costs. The thermal power plant operation is dependent upon incineration of fossil fuel which generates SOx, NOx and COx emission. The increasing pollution is a matter of environmental concern worldwide which has led to formation of international standards for emissions from industries and power plants. Different acts have been made which forces the industries to modify their principles to follow the environment-emission standards strictly. Therefore it is significant to consider emission constraint in economic dispatch. The economic & emission dispatch are contradictory in character and both must be considered together to find optimal dispatch. The problem is formulated as a multiobjective economic emission load dispatch (EELD) problem in which both the objectives (emission and economy) have to be minimized.

Earlier traditional methods like Newton's method, gradient approach and linear programming [1] were used for solving ELD problem. In the last years different techniques have been used for solving EELD. Nanda et.al [2] applied goal programming techniques for solving EELD. Song et.al [3] solved environmental/economic dispatch with genetic algorithm controlled by fuzzy logic. Abido [4] used genetic algorithm for the EELD to find out pareto-optimal solutions. Ah King [5, 6] applied improved non-dominated sorting genetic algorithm (NSGA-II) for creating pareto-optimal front for EELD. Thenmozhi [7] solved EELD using hybrid genetic algorithm. Perez [8] solved environmental/economic dispatch using differential evolution. Hong [9] applied immune genetic algorithm for EELD. Hazra [10] proposed bacteria foraging algorithm for emission constrained economic dispatch. Hemamalini [11] solved non convex EELD by applying particle swarm optimization.Bhattacharya.et.al [14] presented a BBO technique to solve EELD of thermal generators with different emission substances (SOx, NOx, & COx). Similarly there are many other techniques like teaching learning based algorithm [15,firefly algorithm (FFA) [16] and artificial neural networks [17],NSGA [21], SPEA [22],PSO[23], bacterial foraging algorithm with fuzzy logic[24] and Ant lion optimization[27] which have been successfully used to solve EELD problem.GWO has been earlier applied to solve single objective ELD [26].

In this paper combined emission and economic dispatch problem has been transformed to single objective problem by using cost penalty factors. After that grey wolf optimization (GWO) is used to solve the modified problem.

II. PROBLEM FORMULATION

2.1 Economic Load Dispatch

Aim for economic dispatch is to reduce the operating (fuel) cost of thermal generators satisfying some limits[27]. The objective function is given by:

$$C = \sum_{i=1}^{NG}(a_i P_{gi}^2 + b_i P_{gi} + c_i) \qquad \dots (1)$$

Where a_i, b_i, & c_i are the fuel-cost coefficients and P_{gi} is power output for the ith generating unit among NG total committed generating units.

The constraints to be considered are:

a) Energy equality constraint

The overall generation by the entire generators should be equal to the sum of whole power demand (P_d) & system's real power loss (P_L).

$$\sum_{i=1}^{NG} P_{gi} - P_d - P_L \quad \text{... (2)}$$

The power loss P_L is calculated by using generator power output and B coefficients:

$$P_L = \sum_{i=1}^{NG}\sum_{j=1}^{NG} P_i B_{ij} P_j + \sum_{i=1}^{NG} B_{0i} P_i + B_{00} \quad \text{... (3)}$$

b) Generator inequality constraint

Output power of each generator must lie between its lower P_{gi}^{min} and upper P_{gi}^{max} operating limits.

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \quad i=1,2\ldots NG \quad \text{... (4)}$$

2.2 Economic Emission Dispatch

EED objective is to diminish the entire pollution ejection from combustion of coal or gas for producing electricity. The emission function consist of the summation of different types of emissions (i.e. COx, NOx and SOx)with appropriate pricing for every pollutant discharged[27]. The problem of EED for COx, NOx and SOx emissions can be defined by as :

$$E_N = \sum_{i=1}^{NG}(d_{iN}P_{gi}^2 + e_{iN}P_{gi} + f_{iN}) \quad \text{... (5)}$$

$$E_S = \sum_{i=1}^{NG}(d_{iS}P_{gi}^2 + e_{iS}P_{gi} + f_{iS}) \quad \text{... (6)}$$

$$E_C = \sum_{i=1}^{NG}(d_{iC}P_{gi}^2 + e_{iC}P_{gi} + f_{iC}) \quad \text{... (7)}$$

Where E_N ,E_S & E_C are the total amount of NOx, SOx and COx emission from the power plant in (kg/hr.).

The power balance & generator limit restrictions are given by Eq. (2 & 4) respectively.

2.3 Economic emission Load dispatch (EELD) problem

The emission and economic dispatch are contradictory in character and they both have to be considered together to find optimal dispatch. The problem is expressed as a multiobjective EELD problem in which both objectives (emission and economy) [27] have to be minimized.

The objective function is given by: FC (C, E_N, E_S & E_C) … (8)

Where C denote fuel cost objective and E_N,E_S & E_C denote emission objectives.

The multiobjective EELD can be transformed to single objective problem by using cost penalty factors (cpf) denoted by "k". When fuel cost and NOx emissions are considered objective function becomes:

$$FC = C + k_N(E_N) \quad \text{... (9)}$$

When fuel cost, NOx & SOx emissions have to be considered together, the final objective function can be defined as

$$FC = C + k_N(E_N) + k_S \quad \text{... (10)}$$

When fuel cost, NOx, SOx & COx emissions have to be considered together, the final objective function can be defined as

$$FC = C + k_N(E_N) + k_S(E_S) + k_C(E_C) \quad \text{... (11)}$$

Where k_N ,k_S & k_C are price penalty factors for the NOx , SOx & COx emissions ,that combines respective emissions cost with fuel cost.

The steps to calculate price penalty factors for SOx, NOx and COx [19, 25] are given below:

(a) Calculate fuel cost of every generating unit at its highest output, i.e.,

$$C = \sum_{i=1}^{NG}(a_i P_{gi\,max}^2 + b_i P_{gi\,max} + c_i) \quad \text{... (12)}$$

(b) Calculate the SOx, NOx & COx emission discharge for each generator at its max output, i.e.,

$$E_N = \sum_{i=1}^{NG}(d_{iN}P_{gi\,max}^2 + e_{iN}P_{gi\,max} + f_{iN}) \quad \text{... (13)}$$

$$E_S = \sum_{i=1}^{NG}(d_{iS}P_{gi\,max}^2 + e_{iS}P_{gi\,max} + f_{iS}) \quad \text{... (14)}$$

$$E_C = \sum_{i=1}^{NG}(d_{iC}P_{gi\,max}^2 + e_{iN}P_{gi\,max} + f_{iC}) \quad \text{... (15)}$$

(c) k_N [i], k_S [i] & k_C [i] ,(i = 1, 2, …. , NG) is calculated for every generator

$$k_N[i] = \frac{\sum_{i=1}^{NG}(a_i P_{gi\,max}^2 + b_i P_{gi\,max} + c_i)}{\sum_{i=1}^{NG}(d_{iN}P_{gi\,max}^2 + e_{iN}P_{gi\,max} + f_{iN})} \quad \text{... (16)}$$

$$k_S[i] = \frac{\sum_{i=1}^{NG}(a_i P_{gi\,max}^2 + b_i P_{gi\,max} + c_i)}{\sum_{i=1}^{NG}(d_{iS}P_{gi\,max}^2 + e_{iS}P_{gi\,max} + f_{iS})} \quad \text{... (17)}$$

$$k_C[i] = \frac{\sum_{i=1}^{NG}(a_i P_{gi\,max}^2 + b_i P_{gi\,max} + c_i)}{\sum_{i=1}^{NG}(d_{iC}P_{gi\,max}^2 + e_{iN}P_{gi\,max} + f_{iC})} \quad \text{... (18)}$$

(d) Organize k_N [i], k_S [i] & k_C [i] in increasing direction.

(e) Add max output of every generator (Pi max) single at a time, start from minimum k_N [i], k_S [i] & k_C [i] for NOx , SOx & COx emissions until $\sum P_{i\,max} \ge P_d$

(f) On this point k_N [i], k_S [i] & k_C [i] related with final generator in the procedure are the price penalty factor k_N, k_S & k_C for the NOx, SOx & COx emission for that demand P_d.

III. GREY WOLF OPTIMIZATION

In this section grey wolf optimization (GWO) is discussed for solving multiobjective EELD problem. Mirjalili et al [25] proposed GWO algorithm which was inspired by social and hunting behavior of grey wolf. The head of pack are a male and female, called alphas (α). The alpha is generally responsible for taking decisions about hunting, time to wake, sleeping place, and so on. Fascinatingly, the alpha is not essentially the strongest member in the pack but the greatest in terms of supervision of the pack. This shows that the discipline and organization of a pack is of a great deal than its strength. In the hierarchy of grey wolves the second level is beta. The betas are secondary wolves that help the alpha in making decisions or other activities of the pack. It maintains discipline in the pack and acts as an advisor to the alpha. The reinforcing of the alpha's orders is done by beta all through the pack and provides feedback to the alpha. Delta (δ) wolves are the third in social hierarchy of grey wolves and they have to submit to betas and alphas, but they govern the omega. Sentinels, scouts, hunters, elders, and caretakers belong to this group. Sentinels shield and promise the protection of the pack. Scouts are accountable for watching the borders of the territory of the pack and warn the pack in case of any threat. Elders are the knowledgeable wolves who used to be beta or alpha. Hunter's assist the betas and alphas when hunting prey plus providing food to the pack. Lastly, the caretakers are in charge for caring for the frail, sick, and injured wolves of the pack. The omega(ω) is ranked lowest among grey wolves. The omega acts like a scapegoat. Omega wolves always have to surrender to all the other governing wolves and are the last wolves that are permitted to eat.

In the mathematical model of the social hierarchy of the grey wolves, alpha (α) is considered as the fittest solution. Accordingly, the second best solution is named beta (β) and third best solution is named delta (δ) respectively. The candidate solutions which are left over are taken as omega (ω). In the GWO, the optimization (hunting) is guided by alpha, beta, and delta. The omega wolves have to follow these wolves.

During hunting prey is encircled by grey wolves which can be modeled mathematically as following equations[25]:

$$\vec{D} = |\vec{C}.\vec{X}_p(t) - \vec{X}(t)| \quad \text{... (19)}$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A}.\vec{D} \quad \text{... (20)}$$

Where $\vec{A}$ and $\vec{C}$ are constant vectors, $\vec{X}_p$ is prey's location vector, $\vec{X}$ denotes grey wolf's location vector and 't' is present iteration.

$\vec{A}$ and $\vec{C}$ vectors are computed as follows [25]:

$$\vec{A} = 2.\vec{a}.\vec{r}_1.\vec{a} \quad \text{..... (21)}$$

$$\vec{C} = 2.\vec{r}_2 \quad \text{... (22)}$$

'$\vec{a}$ 'is reduced linearly from 2 to 0 during iterations and r1, r2 are random vectors in [0, 1] gap. Wolves are forced to attack upon the prey when |A| < 1 and diverge from the prey when |A| > 1 to optimistically find a better prey.

The hunt is normally directed by alpha, beta and delta, which have greater knowledge about the feasible site of prey. The other wolves must amend their position according to best wolf position. The equations used for wolves position updating are given below [25]:

$$\begin{bmatrix} \vec{D}_\alpha = |\vec{C}_1.\vec{X}_\alpha - \vec{X}| \\ \vec{D}_\beta = |\vec{C}_2.\vec{X}_\beta - \vec{X}| \\ \vec{D}_\delta = |\vec{C}_3.\vec{X}_\delta - \vec{X}| \end{bmatrix} \quad \text{... (23)}$$

$$\begin{bmatrix} \vec{X}_1 = \vec{X}_\alpha - \vec{A}_1.(\vec{D}_\alpha) \\ \vec{X}_2 = \vec{X}_\beta - \vec{A}_2.(\vec{D}_\beta) \\ \vec{X}_3 = \vec{X}_\delta - \vec{A}_3.(\vec{D}_\delta) \end{bmatrix} \quad \text{.... (24)}$$

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \quad \text{...... (25)}$$

IV. SIMULATION TESTS AND RESULTS

In this paper multi-objective economic load dispatch has been solved for three different test systems. In all cases, the constraints of operating limit and power balance are considered. The program was written in MATLAB (R2009b).The population (i.e. number of grey wolves) taken in each case was 30 and maximum number of iterations performed were 500.

1) Test system 1

In this case system having 3 generating units considering NOx emissions is tested to reveal effectiveness of GWO.Theinput data, such as cost &emission coefficients, loss data, generation restrictions, istaken from [19]. The power demands are 300,500 and 700 MW. The best negotiating results achieved from GWO are shown in table 1 and their comparison with other techniques is shown in table 2.

Table.1: EELD with NOx emission for 3-unit system

	Load Demand		
	300	**500**	**700**
Unit 1	49.31	128.82	182.61
Unit 2	130	191.47	270.36
Unit 3	125	191.38	270.35
j_N (Rs/Kg)	43.1703	44.8063	47.8218

Fuel cost(Rs/hr)	16378.37	25494.84	35462.78
Emission(Kg/hr)	135.24	311.12	651.50
Power loss(MW)	4.318	11.67	23.33
Total cost(Rs/hr)	22218.372	39435.338	66619.07

Table.2: Comparison of results for 3-unit system for 700MW load demand

Pf_N (Rs/Kg)	Performance	Conventional Method [12]	SGA [12]	RGA [12]	FFA[20]	GWO
47.8218	Fuel cost, Rs/hr	35485.05	35478.44	35471.4	35464	35462.78
	Emission, kg/hr	652.55	652.04	651.60	651.5	651.50
	Power loss, MW	23.37	23.29	23.28	23.36	23.33
	Total cost, Rs/hr	66690	66659	66631	66622.6	66619.07

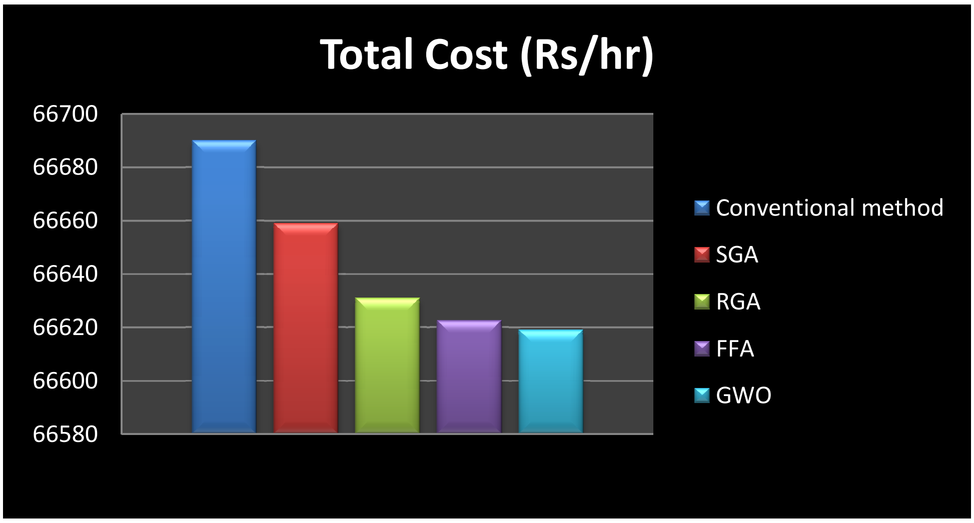

Fig.1: Comparison results for 3-Unit system with 700MW demand

2) Test system 2

In this test case a system with 6 generating units with NOx emissions is used to reveal the effectiveness of GWO for this type of system. The unit's data, such as cost & emission coefficients, B-loss coefficients, generation limits, are given in [19]. The load demands are 500,700 and 900 MW. The best compromising results achieved from GWO are shown in table 3 and their comparison with other techniques is shown in table 4.

Table.3: Best compromise solution of fuel cost and NOx emission for six-generator system

	Load Demand		
	500	**700**	**900**
Unit 1	33. 137	61.855	92.352
Unit 2	26. 821	61.382	98.373
Unit 3	89.928	120.030	150.087
Unit 4	90.553	119.577	148.457
Unit 5	135.805	178.564	220.423

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Unit 6	132.689	175.654	218.320
Pf_N (Rs/Kg)	43.1533	43.8983	47.822
Fuel cost(Rs/hr)	27612.23	37493.95	48350.41
Emission(Kg/hr)	263.03	439.764	693.79
Power loss(MW)	8.93	17.064	28.013
Total cost(Rs/hr)	38963.10	56798.88	81529.18

Table.4: Comparison of best compromise solution of fuel cost and NOx emission for six-generator system(900 MW demand)

Performance	Conventional Method [13]	RGA [13]	Hybrid GA [13]	Hybrid GTA [13]	FFA[20]	GWO
Fuel cost, Rs/hr	48892.900	48567.7	48567.5	48360.9	48353.4	48350.41
Emission, kg/hr	701.428	694.169	694.172	693.570	693.729	693.79
Power loss, MW	35.230	29.725	29.718	28.004	28.004	28.013
Total cost, Rs/hr	82436.580	81764.5	81764.4	81529.1	81529.01	81529.1

3) Test system 3

In this case system having 3 generating units considering NOx and SOx emissions is tested. The input data for generating units is taken from [5]. The power demandis 850MW. The best negotiating results achieved from GWO and its comparison with NSGA-II [5] is shown in table 5.

Table.5: EELD with NOx& SOxemission for 3-unit system with load demand of 850 MW

Unit Power Output	Combined economic emission dispatch solution	
	NSGA-II [6]	GWO
P1(MW)	496.328	506.7511
P2(MW)	260.426	252.0804
P3(MW)	108.144	105.9419
Total power output(MW)	864.898	864.7734
Ploss (MW)	14.898	14.769
Fuel Cost ($/hour)	8358.896	8364.148517
SOX Emission (Ton/hour)	8.97870	8.9743
SOX Price Penalty Factor($/Ton)	970.031570	970.0316
NOX Emission (Ton/hour)	0.09599	0.095925
NOX Price Penalty Factor($/Ton)	147582.78814	147582.78814
Total Cost ($/hour)	31234.99029	31226.91617

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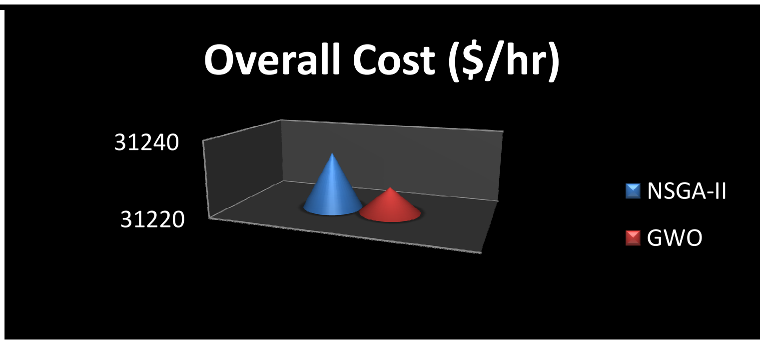

Fig.2: Comparison results for 3-generating units with NOx & SOx emission

4) Test system 4

A system with 6 generating units considering SOx, COx and NOx emissions is tested .The input data for generating units is taken from [18]. The power demand is 1800 MW. The compromised results achieved from GWO and its comparison with PSO [18] and BBO [14] is shown in table 6.

Table.6: EELD with SOx, NOx and COx emission for 6-unit system with load demand of 1800 MW

Unit power output	Combined economic emission dispatch solution		
	PSO [18]	**BBO[14]**	**GWO**
P1 (MW)	279.19	270.398419	270.4809687
P2 (MW)	350.52	299.351832	299.4672109
P3 (MW)	467.90	538.382133	538.2400654
P4 (MW)	176.26	139.632475	139.6657591
P5 (MW)	394.74	452.562062	452.3213489
P6 (MW)	256.20	245.197113	245.3152183
Total power output (MW)	1924.81	1945.524034	1945.490571
P loss (MW)	124.81	145.524034	145.490571
Fuel cost ($/hr)	18689.01	18934.704952	18934.20964
NOX emission (kg/hr)	2432.25	2416.130219	2415.944898
NOX PPF ($/kg)	9.362740	9.362740	9.362740
SOX emission (kg/hr)	14620.07	13491.924811	13492.71155
SOX PPF ($/kg)	1.670211	1.670211	1.670211
COX emission (kg/hr)	62856.00	68817.333954	68804.24931
COX PPF ($/kg)	0.244623	0.244623	0.244623
Total cost ($/hr)	81256.159388	80924.967912	80925.01058

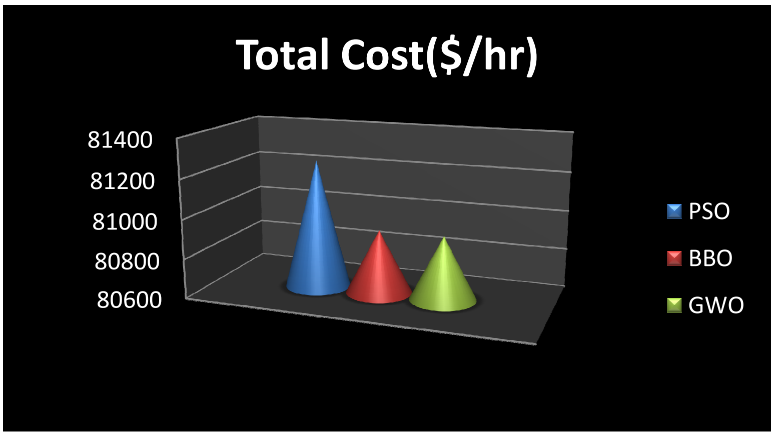

Fig.3: Comparison results for 6 generating units considering SOx, Cox & NOx emissions

V. CONCLUSION

The GWO algorithm is effectively applied for solving multi-objective EELD problem. It is apparent from the obtained results that the proposed GWO algorithm can evade the deficiency of early convergence of the genetic algorithm and particle swarm optimization methods to get superior solutions. The results confirmed that GWO was able to give competitive results in comparison to GA, hybrid GA, PSO, FFA and BBO. The novel probabilistic model of searching, encircling and hunting the prey handle the trouble of early convergence. Because of simplicity and effectiveness of the GWO method, it can be useful for searching better results in difficult power system problems in future.

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