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Imperialist Competition Algorithm for Solving Non-convex Dynamic Economic Power Dispatch

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Abstract

Dynamic economic dispatch (DED) aims to schedule the online generating units' output active power most economically over a certain period of time, satisfying operational constraints and load demand in each interval. Valve-point effect, the ramp rate limits, prohibited operation zones (POZs), and transmission losses make the DED a complicated, non-linear and constrained problem. Hence, in this paper, Imperialist Competition Algorithm (ICA) is used to solve such complicated problem. The feasibility of the proposed method is validated for five and ten units test system for a 24 hour time interval. Results obtained with the proposed approach are compared with other techniques in the literature. The results obtained substantiate the applicability of the proposed method for solving the constrained DED with non-smooth cost functions.

I. INTRODUCTION

Generally, the economic dispatch of power system can be categorized into static economic dispatch (SED) and dynamic economic dispatch (DED). The SED optimizes the system objective function (total fuel cost in general) in specified time and does not take into account the fundamental relation of system between the different operating times. The DED takes into account the connection of different operating times by considering ramp rate constraints. The DED is one of the important optimization problems used in power systems to obtain the optimal operation schedule of the committed units over the entire dispatch period.

Considering the dynamic constraints like ramp rate limits makes the DED problem more complicated. One way to simplify the solution of DED is to consider it as sequential SED problems [1] and force the ramp rates between the sequential hours. It is shown that this method would lead into being trapped in a local optimal solution [2]. Generators are modeled using input-output curves in most of the power system operation studies. Traditionally an approximate quadratic function used to model the generator input-output curves [1], [3]. This would result in an inaccurate dispatch. Because the natural input-output curve is nonlinear and non-smooth due to the effect of multiple steam admission valves (known as valve-points effect) [4], [5]. Obtaining the global optimum or better local optimum for non-convex DED problems is a great challenge. Application of the classical methods such as Lagrangian relaxation approach [6] and dynamic programming [7] are restricted [8]. In recent years, Maclaurin Series approximation has been applied to model the valve-point effects [9]–[11] but it has been shown that this method leads to non-optimal solution. Optimization methods based on artificial intelligence has shown better performance in solving the DED problem with capability of modeling more realistic objective function and constraints. In [12], Hybrid evolutionary programming and sequential quadratic programming (SQP) method has been proposed to solve non-convex DED problem. Chiou [13] proposed variable scaling hybrid differential evolution (VSHDE) method for solution of large scale DED problems. Differential evolution algorithm has received a great deal of attention in solving DED problems [14]–[20]. Other stochastic search methods have been applied to solve DED problems in the past decade. These include genetic algorithm [21], quantum genetic algorithm [22], artificial immune system method [23], artificial bee colony algorithm [8], particle swarm optimization [24]–[27], multiple tabu search algorithm [28], enhanced cross-entropy method [29], simulated annealing algorithm [30]. Hybrid methods such as hybrid artificial immune systems and sequential quadratic programming [31], hybrid EP and SQP method [12], [32], hybrid swarm intelligence based harmony search algorithm [4], hybrid seeker optimization algorithm (SOA) and sequential quadratic programming (SQP) [33], hybrid hopfield neural network (HNN) and quadratic programming (QP) [34], [35], adaptive hybrid differential evolution algorithm [36] and hybrid particle swarm optimization and sequential quadratic programming [37] are found to be more effective in solving complex optimization problems such as DED problem. In this paper, an Imperialist Competition Algorithm (ICA) is proposed to solve non-convex dynamic economic dispatch problem with constraints. More details of the proposed algorithm are provided in Section III. The remainder of the paper is organized as follows: Section II gives the mathematical formulation of the DED problem considering POZs, ramp-rate limits, valve-point effects and transmission losses. Section III describes the proposed algorithm. Section IV presents four application cases and gives the corresponding comparison results with the most recent applied methods. Conclusions are finally given in Section V.

II. DYNAMIC ECONOMIC DISPATCH PROBLEM FORMULATION

The objective function of DED problem is to minimize the total production cost over the operating horizon, which can be written as:

$$\min TC = \sum_{t=1}^{T}\sum_{i=1}^{N} C_{it}(P_{it}) \qquad (1)$$

Where C_{it} is the unit i production cost at time t, N is the number of dispatchable power generation units and P_{it} is the power output of i-th unit at time t. T is the total number of hours in the operating horizon. The production cost of generation unit considering valve-point effects is defined as:

$$C_{it}(P_{it}) = a_i P_{it}^2 + b_i P_{it} + c_i + |\, e_i \sin(f_i (P_i^{min} - P_{it}))\,| \quad (2)$$

where a_i, b_i, c_i are the fuel cost coefficients of the i-th unit, e_i and f_i are the valve-point coefficients of the i-th unit. $P_{\min}$ is the minimum capacity limit of unit i. It should be noted that the added sinusoidal term in the production cost function reflects the effect of valve-points. The DED problem will be non-convex and non-differentiable considering valve-point effects [38].

The objective function of the DED problem (1) should be minimized subject to the following equality and inequality constraints:

1) Real power balance

Hourly power balance considering network transmission losses is written as:

$$\sum_{i=1}^{N} P_{it} = P_D(t) + P_{loss}(t) \qquad (3)$$

where $P_{loss}(t)$ and $P_D(t)$ are total transmission loss and total load demand of the system at time t, respectively. System loss is a function of units power production and can be calculated using the results of load flow problem [37] or Kron's loss formula known as B− matrix coefficients [34]. In this work, B− matrix coefficients method is used to calculate system loss as follows:

$$P_{loss}(t) = \sum_{i=1}^{N}\sum_{j=1}^{N} P_{it} B_{ij} P_{jt} + \sum_{i=1}^{N} B_{i0} P_{it} + B_{00} \qquad (4)$$

2) Generation limits of units:

$$P_i^{min} \le P_{it} \le P_i^{max} \qquad (5)$$

where P_i^{max} is the maximum power outputs of i-th unit.

3) Ramp up and ramp down constraints: The output power change rate of the thermal unit must be in

an acceptable range to avoid undue stresses on the boiler and combustion equipments [39]. The ramp rate limits of generation units can be mathematically stated as follows:

$$P_{it} - P_{it-1} \le UR_i \qquad (6)$$

$$P_{it-1} - P_{it} \le DR_i \qquad (7)$$

where UR_i is the ramp up limit of the i-th generator (MW/hr) and DR_i is the ramp down limit of the i-th generator (MW/hr). Considering ramp rate limits of unit, generator capacity limit (5) can be rewritten as follows:

$$\max(P_i^{min}, P_{it-1} - DR_i) \le P_{it} \le \min(P_i^{max}, P_{it-1} + UR_i) \qquad (8)$$

4) Prohibited Operation Zones limits (POZs): Generating units may have certain restricted operation zone due to limitations of machine components or instability concerns. The allowable operation zones of generation unit can be defined as:

$$P_{it} \in \begin{cases} P_i^{min} \le P_{it} \le P_{i,1}^{l} \\ P_{i,j-1}^{u} \le P_{it} \le P_{i,j}^{l}, & j = 2,3,\dots,M_i, \\ P_{i,M_i}^{u} \le P_{it} \le P_i^{max} & i = 1,\dots,N,\ t = 1,2,\dots,T \end{cases} \qquad (9)$$

where $P_{i,j}^{l}$ and $P_{i,j}^{u}$ are the lower and upper limits of the j^{th} prohibited zone of unit i, respectively. M_i is the number of prohibited operation zones of unit i.

III. IMPERIALIST COMPETITION ALGORITHM (ICA)

The Imperialist Competition Algorithm (ICA) was first proposed in [40]. It is inspired by the imperialistic competition. It starts with an initial population called colonies. The colonies are then categorized into two groups namely, imperialists (best solutions) and colonies (rest of the solutions). The imperialists try to absorb more colonies to their empire. The colonies will change according to the policies of imperialists. The colonies may take the place of their imperialist if they become stronger than it (propose a better solution). This algorithm has been successfully applied to PSS design [41] and data clustering [42]. The flowchart of proposed algorithm is depicted in Fig.1. The steps of the proposed ICA are described as follows:

Step 1. Generate an initial set of colonies with a size of N_C.

Step 2. Set Iteration=1.

Step 3. Calculate the objective function for each colony using (2) and set the power of each colony as Follows

$$CP_c = OF \qquad (10)$$

This means the less OF is, the more stronger IP_i is.

Step 4. Keep the best N_{imp} colonies as the imperialists and set the power of each imperialist as follows:

$$IP_i=OF \qquad (11)$$

Step 5. Assign the colonies to each imperialist according to calculated IP_i. This means the number of colonies owned by each imperialist is proportional to its power, i.e. IP_i.

$$\frac{IP_i}{\sum_{j=1}^{N_{imp}} IP_j}\times(N_c-N_{imp})$$

Step 6. Move the colonies toward their relevant imperialist using crossover and mutation operators.

Step 7. Exchange the position of a colony and the imperialist if it is stronger (CP_c > IP_i).

Step 8. Compute the empire's power, i.e. EP_i for all empires as follows:

$$EP_i=\frac{1}{N_{E_i}}\times(w_1\times IP_i+w_2\times\sum_{c\in E_i}CP_c) \qquad (12)$$

where w_1 and w_2 are weighting factors which are adaptively selected.

Step 9. Pick the weakest colony and give it to one of the best empires (select the destination empire probabilistically based on its power (EP_i).

Step 10. Eliminate the empire that has no colony.

Step 11. If more than one empire remained then go to Step. 6

Step 12. End.

The flowchart of the proposed Algorithm is depicted in Fig.1.

IV. CASE STUDIES AND NUMERICAL RESULTS

In this section, the proposed ICA is applied on four test systems with different number of generating units. After a number of careful experimentation, following optimum values of ICA parameters have finally been settled: N_C = 100; crossover probability = 0.6, mutation probability=0.2 . For all cases, the dispatch horizon is selected as one day with 24 dispatch periods of each one hour. The hourly load profiles for all cases are presented in Table I. The stopping criteria is defined as reaching to the maximum number of iterations (here 600 iterations) or when no significant changes observed in the objective function.

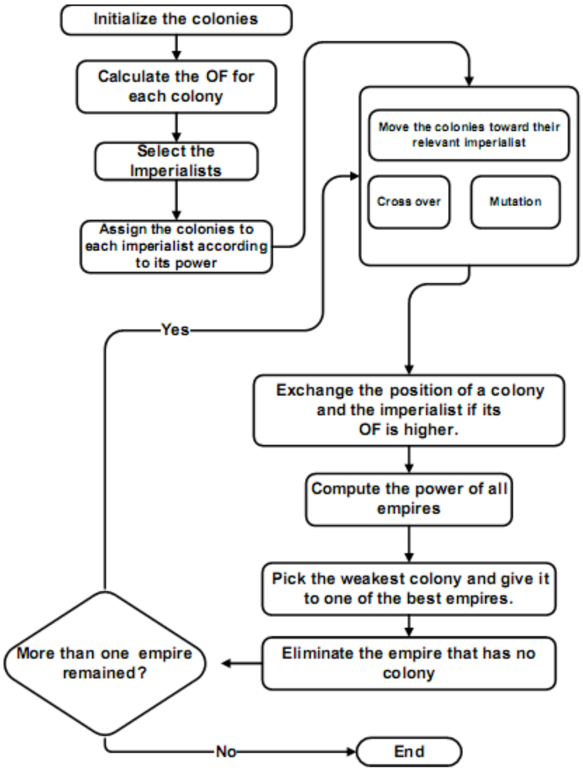

Fig. 1. The flowchart of the proposed algorithm

A. Case 1: Five unit system

The first test system is a 5-unit test system. The data for this system is provided in [30]. In this test system, transmission losses and ramp rate constraints are considered. The B−matrix coefficients of this system are given in [30].

The DED problem of 5-unit system is solved using proposed algorithm. The valve-point effects, transmission losses, ramp rate constraints and generation limits are considered in this system. The prohibited operating zones are not considered in this test case for the sake of comparison of results with those reported in literature using different methods. Table III shows the obtained results for this system. These results are compared with adaptive particle swarm optimization (APSO) algorithm [24], simulated annealing (SA) algorithm [30], artificial immune system (AIS) [23], maclaurin series based Lagrangian method

(MSL) [10], genetic algorithm (GA) [8], particle swarm optimization (PSO) [8], artificial bee colony (ABC) algorithm [8], in Table III.

TABLE I: HOURLY LOAD PROFILE FOR CASE STUDY SYSTEMS.

Hour	Case 1	Case 2	Hour	Case 1	Case 2
1	410	1036	13	704	2072
2	435	1110	14	690	1924
3	475	1258	15	654	1776
4	530	1406	16	580	1554
5	558	1480	17	558	1480
6	608	1628	18	608	1628
7	626	1702	19	654	1776
8	654	1776	20	704	2072
9	690	1924	21	680	1924
10	704	2072	22	605	1628
11	720	2146	23	527	1332
12	740	2220	24	463	1184

The maximum iteration number is selected to be 1500. The convergence characteristic of the proposed algorithm is depicted in Fig. 2. By investigating the results presented in Table III, it can be observed that the obtained results outperform the existing methods.

**TABLEII
OPTIMAL SOLUTION OF 5-UNIT
USING PROPOSED ALGORITHM.**

Hour	P1	P2	P3	P4	P5	Cost($)	Loss(MW)
1	10	20	30	124.485	229.504	1226.587	3.989
2	19.078	20	30	140.846	229.520	1418.346	4.444
3	10	20	30	190.846	229.519	1493.566	5.365
4	10	20	67.023	209.816	229.520	1662.802	6.359
5	10	20	95.511	209.816	229.515	1667.456	6.842
6	13.949	50	112.675	209.816	229.520	1826.620	7.960
7	10	72.451	112.673	209.816	229.520	1840.605	8.460
8	12.709	98.54	112.674	209.815	229.520	1797.229	9.258
9	42.709	102.78	115.353	209.817	229.520	2013.697	10.179
10	64.03	98.54	112.671	209.799	229.519	1996.680	10.559
11	75	98.791	117.878	209.816	229.520	2039.988	11.005
12	75	124.71	112.674	209.816	229.521	2180.027	11.721
13	64.012	98.54	112.673	209.816	229.520	1996.599	10.561
14	49.62	98.54	112.673	209.816	229.519	1977.667	10.168
15	35.892	98.54	112.673	186.5	229.520	2010.648	9.125
16	10	98.54	112.674	136.5	229.520	1682.800	7.234
17	10	87.586	112.672	124.905	229.519	1615.305	6.682
18	10	98.54	112.674	165.218	229.520	1853.472	7.952
19	12.709	98.54	112.674	209.816	229.520	1797.224	9.259
20	42.709	119.939	112.674	209.816	229.520	2115.511	10.658
21	39.353	98.54	112.674	209.816	229.520	1944.597	9.903
22	10	98.541	110.204	164.619	229.520	1860.868	7.884
23	10.001	98.54	70.204	124.908	229.520	1643.076	6.173
24	10	73.366	30.204	124.908	229.519	1455.677	4.997
Total						**43117.05**	**196.737**

**TABLEIII
COMPARISONOFOPTIMIZATIONRESULTSFOR
5-UNITTEST SYSTEM (CASE 1).**

Method	Best Cost($)
SA[30]	47356
APSO[24]	44678
AIS[23]	44385.43
MSL[10]	49216.81
GA[8]	44862.42
PSO[8]	44253.24
ABC[8]	44045.83
Proposed	**43117.05**

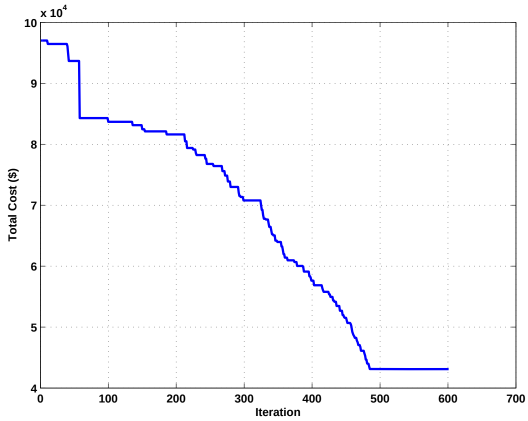

Fig.2.Convergence characteristics of the ICA algorithm for 5-unit test system

B. Case 2: Ten unit system without transmission loss

The second test system is ten-unit test system. In this case, generators capacity limits, ramp rate constraint and valve-point effects are considered. The transmission losses are ignored in this case for sake of comparison. The data for this system is adapted from [30]. Table IV shows the obtained results for 10-unit system without considering transmission losses. The obtained optimal results are compared with results of previously developed algorithm s such as differential evolution (DE) [16], hybrid EP and SQP [12], Hybrid PSO-SQP [37], deterministically guided PSO (DGPSO) [25], modified hybrid EP-SQP (MHEP-SQP) [32], improved PSO (IPSO) [26], Hybrid DE (HDE) [17], Improved DE (IDE) [18], artificial bee colony Algorithm (ABC) [8], modified differential evolution (MDE) [19], covariance matrix adapted evolution strategy (CMAES) [43], artificial immune system (AIS) [23], hybrid swarm intelligence based harmony search Algorithm (HHS) [4], improved chaotic particle swarm optimization Algorithm (ICPSO) [27], hybrid artificial immune systems and sequential quadratic programming (AIS-SQP) [31], hybrid SOA-SQP Algorithm [33], chaotic sequence based differential evolution Algorithm (CS-DE) [14], chaotic differential evolution (CDE) method [20], adaptive hybrid differential evolution Algorithm (AHDE) [36], and enhanced cross-entropy method (ECE) [29] in Table V. The maximum iteration number is selected to be 2000. The convergence characteristic of the proposed Algorithm is depicted in Fig. 3. It can be evidently observed that the obtained results with ICA Algorithm is less than those of reported in literature.

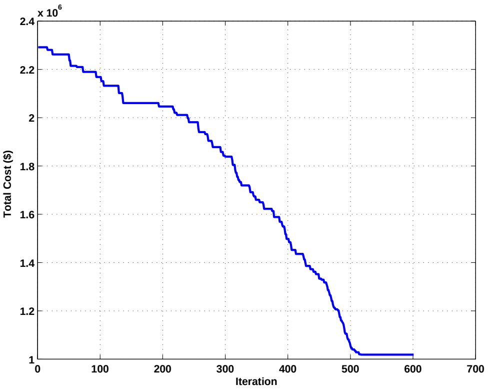

Fig.3.Convergence characteristics of the ICA algorithm for 10-unit test system

TABLE IV: OPTIMAL 24-HOURSCHEDULEOFTEN-UNITTESTSYSTEM (CASE 2).

Hour	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Cost($)
1	150	135	194.065	60	122.88	122.46	129.594	47	20	55	28238.754
2	226.624	135	191.461	60	122.867	122.457	129.591	47	20	55	29828.077
3	303.249	142.266	185.208	60	172.733	142.546	129.997	47	20	55	33347.045
4	379.874	222.266	196.603	60	172.733	122.526	129.997	47	20	55	36296.715
5	379.868	222.266	183.675	60	222.6	160	129.59	47	20	55	37991.334
6	455.434	302.266	263.674	60	172.601	122.434	129.59	47	20	55	41387.159
7	379.898	309.534	305.892	110	222.601	122.481	129.594	47	20	55	42844.529
8	456.497	316.799	297.946	120.418	172.747	160	129.593	47	20	55	44600.484
9	456.497	396.799	303.71	132.802	222.6	160	129.59	47	20.002	55	47885.318
10	456.497	460	297.781	182.802	233.328	160	129.59	47	50.002	55	51887.342
11	456.491	460	300.462	232.802	222.598	159.999	129.59	77	52.057	55	53788.277
12	456.498	460	318.192	282.802	222.6	160	129.594	85.312	50.002	55	55605.118
13	456.497	396.8	307.935	238.264	222.6	160	129.59	85.312	20.002	55	51357.359
14	456.446	396.799	297.407	188.264	172.733	122.45	129.59	85.312	20	55	47818.061
15	379.872	393.192	297.301	170.448	122.863	122.421	129.59	85.312	20	55	44649.659
16	303.251	313.192	331.753	120.449	73	122.451	129.592	85.312	20	55	39816.706
17	226.624	309.533	295.168	113.568	122.755	122.449	129.59	85.312	20	55	37983.869
18	303.248	315.523	303.703	120.416	172.751	122.456	129.59	85.312	20	55	41294.355
19	379.872	395.523	295.242	120.341	172.671	122.448	129.59	85.312	20	55	44374.06
20	456.512	460	340	170.341	222.671	132.571	129.592	85.312	20	55	51862.515
21	456.497	389.533	322.67	120.342	222.604	122.45	129.591	85.312	20	55	47915.54
22	379.85	309.533	283.231	70.342	172.707	122.435	129.59	85.312	20	55	41280.418
23	303.249	229.533	203.235	60	122.867	123.214	129.59	85.312	20	55	34952.455
24	226.639	222.267	189.711	60	73	122.481	129.591	85.312	20	55	31462.345
Total											**1018467.49**

TABLE V

COMPARISON OF OPTIMIZATION RESULTS FOR CASE 2.

Method	Best Cost ($)
DE [18]	1019786
EP-SQP[25]	1031746
PSO-SQP[29]	1027334
DGPSO [13]	1028835
MHEP-SQP [26]	1028924
IPSO [14]	1023807
HDE [19]	1031077
IDE [20]	1026269
ABC [6]	1021576
MDE [21]	1031612
CMAES [15]	1023740
AIS [10]	1021980
HHS [3]	1019091
AIS-SQP[11]	1029900
CS-DE [16]	1023432
CDE [22]	1019123
proposed	**1018467.49**

V. CONCLUSION

In this paper, the ICA approach has been applied to solve the DED problem of generating units considering the valve-point effects, prohibited operation zones (POZs), ramp rate limits and transmission losses. The effectiveness of the proposed Algorithm was verified using DED problems of different dimensions and complexities. Numerical experiments show that the proposed method can obtain better quality solution with higher precision and convergence property, so it provides a new method to solve DED problem.

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