Application of Imperialist Competitive Algorithm to Solve Constrained Economic Dispatch

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Abstract: In the constrained dynamic ED problem, considering some practical operation constraints of generators, such as ramp rate limits and prohibited operating zones, electric power generation of units are scheduled. So, this paper, considering these constraints, presents a new optimization technique based on Imperialist Competitive Algorithm (ICA) to solve the Economic Dispatch (ED) problem in power systems. To show the efficiency of the proposed method, this algorithm is applied to solve constrained dynamic ED problem of two power systems with 6 and 15 units. The results are compared to those achieved from conventional methods such as Simulated Annealing (SA), Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). The experimental results show that the proposed method is capable to determine the solutions of ED problem more fast and accurate than other conventional approaches.

Keywords: Economic Dispatch, Optimization, Imperialist Competitive Algorithm (ICA)

1. Introduction

One of the fundamental cases in power system operation is Economic Dispatch (ED) problem. It should be an optimization problem to reduce the operation cost of units while satisfying constraints. Two types of methods are used to optimize the generation output of units. The first type of methods employed various mathematical programming techniques. These conventional methods include the lambda-iteration method, the base point and participation factors method, the gradient method and etc. [1-3]. To use these kinds of methods for solving ED problem, the main assumption is that the incremental cost curves of the units are increased linearly. However, in practical systems considering the nonlinear characteristics of generators, this assumption is not acceptable. In addition, in a large system the methods based on mathematical programming have oscillatory problem [4].

Noted methods (mathematical methods) usually used to solve one type of ED problem known as static ED problem. The second type of ED problem is known as dynamic ED problem.

The objective function of dynamic ED is to determine generator output considering power balance, generating unit capacity limits, prohibited operating zones, valve point effect and multiple fuel cost. To solve the second type of ED problem (dynamic ED problem), random search optimization methods, such as Evolutionary Programming (EP) [5], Hybrid Immune Genetic Algorithm (HIGA) [6], Tabu Search (TS) [7] and Particle Swarm Optimization (PSO) [4] have been used.

Most of the random search optimization methods have two important problems:

1. Trapping in local minima.
2. Slow rate of convergence.

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To prevent these kinds of problem, this paper proposes the use of a new evolutionary algorithm known as Imperialist Competitive Algorithm (ICA) to solve dynamic ED problem.

The ICA is a meta-heuristic optimization method that is based on modeling of the attempts of countries to dominate other courtiers. Like other evolutionary ones, this algorithm starts with an initial population. Populations are in two types: colonies and imperialists that all together form some empires. Imperialistic competition among these empires forms the basis of this algorithm. During this competition, weak empires collapse and powerful ones take possession of their colonies. Imperialistic competition converges to a state in which there exists only one empire and its colonies are the same position and have the same cost as the imperialist [8]. In [9] ICA is used for static ED problem. In this paper, this algorithm is applied to solve the constrained ED problem.

The rest of this paper organized as follow:
The mathematic formulation of the dynamic ED problem is presented in section II. The ICA is introduced in section III and the implementation of this algorithm for ED problem is explained in section IV. Finally, in section V, the proposed method is verified by using two different power systems with 6 and 15 units.

2. Problem Formulation

The dynamic ED problem is reviewed here for completeness and to clarify the constraints that are observed.

The objective function of the dynamic ED problem is to schedule the output of generation units to meet the required demand at minimum operating cost while satisfying all units' constraints. So, it can be said as follow:
The objective function of the ED problem can be expressed as [10]:

$$\min F_t = \sum_{i=1}^{n} F_i(P_i) = \sum_{i=1}^{n} (a_i + b_i P_i + c_i P_i^2) \tag{1}$$

where F_t is the total operation cost; F_i is the generation cost function of the *i*th generator, a_i, b_i and c_i are the coefficients of cost function of the *i*th generator; P_i is the output power of the *i*th generator and n is the number of generators.
The main equality constraint is the constraint of power balancing which can be expressed as follow:

$$\sum_{i=1}^{n} P_i = P_D + P_L \tag{2}$$

where *PD* is the load demand and *PL* is the total transmission losses, which is a function of the unit power outputs that can be represented as follow:

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{n} B_{0i} P_i + B_{00} \tag{3}$$

where B is matrix that depends on transmission lines parameters.
To achieve the actual economic operation, two inequality constraints of generator are taken into account [10].

Firstly, the ramp rate restrictions of generators are caused in view of the fact that the thermal generating outputs cannot be adjusted quickly. To consider the operating process, the ramp rate limits are included in the ED problem to make sure the feasibility of the solutions.

As a result, the inequality constraints because of ramp rate limits for unit generation changes are presented as follow:

$$\max(P_i^{\min}, P_i^0 - DR_i) \le P_i \le \min(P_i^{\max}, P_i^0 + UR_i) \tag{4}$$

where P_i^0 is the previous output power, P_i^{min} and P_i^{max} are the minimum and maximum outputs of the ith generator, respectively. URi, DRi are the up ramp and down ramp limits of the ith generator.

Secondly, the prohibited operating zones in the performance curve of a typical thermal unit are because of steam valve operation or fluctuation in a shaft bearing [11]. Practically, the shape of the input–output curve in the neighborhood of the prohibited zone is difficult to be determined by actual performance testing or operating records. In the actual operation, adjusting the generation output P_i of a unit must avoid the unit operating in the prohibited zones. The feasible operating zones of unit i can be presented as follows:

$$P_i \in \begin{cases} P_i^{\min} \le P_i \le P_{i,1}^l \\ P_{i,j-1}^u \le P_i \le P_{i,j}^l \qquad j = 2,3,\dots,n_i \\ P_{i,n_i}^u \le P_i \le P_i^{\max} \end{cases} \tag{5}$$

where n_i is the number of prohibited zones of the ith generator. $P_{i,j}^{\ l}$; $P_{i,j}^{\ u}$ are the lower and upper power output of the prohibited zones j of the ith generator, respectively.

3. Imperialist Competitive Algorithm

Imperialism is the policy of spreading the power of an imperial beyond its own boundaries. An imperialist dominate other countries by direct rule or by less obvious means such as control of market for goods or raw materials.

The Imperialist Competitive Algorithm (ICA) was proposed by Esmaeil and Caro [8], this method is a new socio-politically motivated global search strategy that has recently been introduced for dealing with different optimization tasks. In [10], this algorithm is used to find the optimized weights of artificial neural network. Moreover, [12, 13] design an optimal controller using this algorithm.

Figure 1 shows the flow chart of the ICA [8]. Like the same evolutionary algorithms, ICA commences with an initial population of P countries which are generated randomly within the feasible space. Each country is shown by $country_i=[p_1, p_2, \dots, p_{Nvar}]$ which N_{var} is dimension of optimization problem. The best countries in the initial population, considering the cost function of them, are selected as the imperialists and other counties known as the colonies of these imperialists.

To build initial empires, colonies are divided among imperialists Based on imperialist's power. To divide the colonies among imperialists proportionally, the following normalized cost of an imperialist is defined:

$$C_n = c_n - \max(c_i) \tag{6}$$

Where c_n is the cost of nth imperialist and C_n is the normalized cost. As a result the normalized power of each imperialist can be defined:

$$p_n = \left| \frac{C_n}{\sum_{i=1}^{N_{imp}} C_i} \right| \tag{7}$$

After dividing colonies among imperialists, these colonies start closing to their empire. The total power of an empire can be determined by the power of imperialist country plus a percentage of power of its colonies as follow:

$$power_n = \cos t(imperialists_n) + \varepsilon mean\{(\cos t(colonies\ of\ empires_n)\} \tag{8}$$

The way by which the colonies move toward empires can be found in [8].

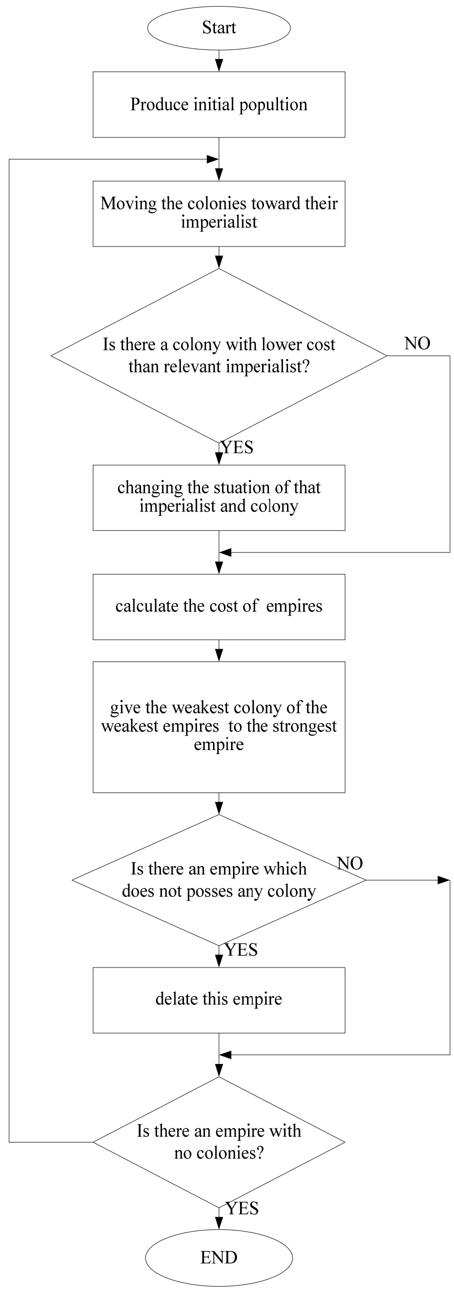

Figure 1. Flow chart of the ICA

Where $power_n$ is the total power (cost) of the nth empire and ξ is a positive number less than 1. Considering [8], its amount is set to 0.1.

After starting competition, any empire that cannot succeed in this competition and cannot increase its power will be eliminated from the competition. The results of competition will be an increase in the power of strong empires and a decrease in the power of weak ones. With passing computation, Weak empires will lose their power and they will collapse. At the end, by using the movement of colonies toward their relevant imperialist and also the collapse mechanism, one imperial will exit which is the answer of optimization problem.

4. Application Of ICA To ED Problem

In this section the implementation of the ICA for solving dynamic ED problem is described.

To apply this algorithm to ED problem, two mechanisms should be specified.

A. Initialization and structure of solutions
B. Constraints handling

These two mechanisms can be used as follow in ICA to determine optimized output of generating units in ED problem.

A. Initialization and structure of solutions

In the initialization process, several initial solutions are created randomly for the ICA. If the initial population of the ICA (countries) considered as the output generation value of units (P_{j1}^0, P_{j2}^0, …, P_{jn}^0). j=1,….., m. where m is the number of countries in ICA and n is the number of generators. To create a set of solutions, equality and inequality constraints should be satisfied. So, the procedure as follow is applied to ICA.

Step (1) read system data

Step (2) the boundary of feasible solution is defined as follow:

$$P_{i\_lower} = \max(P_i^{\min}, P_i^0 - DR_i)$$

$$P_{i\_upper} = \min(P_i^{\max}, P_i^0 + UR_i)$$

Step (3) for i=1: n

$$P_i = P_{i\_lower} + rand() \times (P_{i\_upper} - P_{i\_lower})$$

End

where *rand()* is a uniform random value in the range [0, 1].

B. Constraints handling with ICA

In evolutionary optimization algorithm, handling the existing equality and inequality constraints is very important. In literatures, different methods for handling constraints in evolutionary computation optimization algorithms are presented. The most commonly used constraints handling methods among them are: preserving feasible solution method, infeasible solution rejection method, penalty function method and solution repair method [13]. In this paper the last two methods are used as follow to handle constraint in ICA.

To handle equality constraints in equation (2), penalty function method used as [4]. The evaluation function is adopted as (6), it is reciprocal of the generation cost function F_{cost} and power balance constraints P_{pbc} as in (7) and (8).

$$f = \frac{1}{F_{\cos t} + P_{pbc}} \tag{6}$$

where,

$$F_{cost} = 1 + abs(\frac{(\sum_{i=1}^{n} F_i(P_i) - F_{min})}{(F_{max} - F_{min})} \tag{7}$$

$$P_{pbc} = 1 + (\sum_{i=1}^{n} P_i - P_D - P_L)^2 \tag{8}$$

F_{max} maximum generation cost among all individuals in the initial population;
F_{min} minimum generation cost among all individuals in the initial population.
Moreover, to satisfy the inequality constraint of prohibited zone, solution repair method is used. To prevent solution to fall in the prohibited zone we do as follow:
Step (1): for all units specify prohibited zones (suppose $[a_i^k, b_i^k]$ as the kth prohibited zone of unit i)
Step (2): for each unit

If $a_i^k < P_i < \frac{(a_i^k + b_i^k)}{2}$

$P_i = a_i^k + (a_i^k - b_i^{k-1}) \times rand()$

Else if $\frac{(a_i^k + b_i^k)}{2} < P_i < b_i$

$P_i = a_i^k + (a_i^{k+1} - b_i^k) \times rand()$

End

5. Case Studies

To verify the effectiveness of the ICA for ED problem, two different power systems with 6 and 15 units were tested. Moreover, a comparison is made with SA, GA, HIGA, PSO, TS and MTS that are listed in [4, 6, 10]. The software like in [10] is implemented by the MATLAB language on a on a laptop computer with Core2Duo 2.5 GHz CPU and 2 GByte RAM.
According to the experience, the following parameters are used in the ICA.
Number of countries= 80
Number of imperialist= 8
Maximum iteration= 30
Revolution Rate=0.2
Damp Ratio = 0.99
Uniting Threshold=0.02
Moreover, the parameters of the other optimization methods are listed in [23].

A. 6- generating unit system

The system contains 6 units, 26 buses and 46 lines [4]. The characteristics of the units are listed in Table I. The load demand is 1263 MW. In normal operation of the system, the loss coefficients B matrix with 100 MVA base capacity is shown in [4].

Table 1. Generation unit data of six units system

	P_i^0 *(MW)*	P_i^{min} *(MW)*	P_i^{max} *(MW)*	a_i *($)*	b_i *($/MW)*	c_i *($/MW^2)*	UR_i *(MW/h)*	DR_i *(MW/h)*	Prohibited zones *(MW)*
1	440	100	500	240	7.0	0.0070	80	120	[210,240] [350,380]
2	170	50	200	200	10.0	0.0095	50	90	[90,110] [140,160]
3	200	80	300	220	8.5	0.0090	65	100	[150,170] [210,240]
4	150	50	150	200	11.0	0.0090	50	90	[80,90] [110,120]
5	190	50	200	220	10.5	0.0080	50	90	[90,110] [140,150]
6	110	50	120	190	12.0	0.0075	50	90	[75,85] [100,105]

In [6, 10] six methods (MTS, PSO, HIGA TS, GA and SA) were employed to test on this system. Considering these results and the result of proposed method, Table II elaborates the best solutions of all methods, which satisfy the practical system constraints such as the ramp rate limits and prohibited zones of units. It can be clearly seen in Table II that the solution of the proposed method is the second one which has the minimum cost among all methods. With scheduling the output power of units correctly by the proposed method, the losses of system is decreased; therefore, total cost of system is reduced.

In addition, in Table 3, the statistical results of all methods such as maximum and minimum generation cost, best generation cost and standard deviation are shown. These results are determined after 30 trials.

Table 2. Best solution of six units system

Unit power output	HIGA [6]	SA [10]	GA [10]	TS [10]	PSO [10]	MTS [10]	**ICA**
P_1 *(MW)*	447.399	478.1258	462.0444	459.0753	447.5823	448.1277	**437.9142**
P_2 *(MW)*	173.241	163.0249	189.4456	185. 0675	172.8387	172.8082	**176.5697**
P_3 *(MW)*	263.382	261.7143	254.8535	264.2094	261.3300	262.5932	**265.0000**
P_4 *(MW)*	138.980	125.7665	127.4296	138.1222	138.6812	136.9605	**150.0000**
P_5 *(MW)*	165.392	153.7056	151.5388	154.4716	169.6781	168.2031	**147.8772**
P_6 *(MW)*	87.052	93.7965	90.7150	74.9900	85.8963	87.3304	**97.7552**
Total output	1275.446	1276.1339	1276.0270	1275.94	1276.0066	1276.0232	**1275.1163**
(MW)	12.446	13.1317	13.0268	12.9422	13.0066	13.0205	**12.1168**
P_{loss} (MW)	15443.1	15461.10	15457.96	15454.89	15450.14	15450.06	**15449.06**
Total cost ($/h)							

Table 3. Comparison of ICA performance with other methods for 6 units system

Methods	Maximum cost ($/h)	Average cost ($/h)	Minimum cost ($/h)	Standard deviation
SA [10]	15545.50	15488.98	15461.10	28.3678
GA [10]	15524.69	15477.71	15457.96	17.4072
TS [10]	15498.05	15472.56	15454.89	13.7195
PSO [10]	15491.71	15465.83	15450.14	10.1502
MTS [10]	15453.64	15451.17	15450.06	0.9287
ICA	**15491.71**	**15452.05**	**15449.06**	**2.0458**

B. 15-generating unit system

The second system to verify the proposed method contains 15 units. The characteristics of units are listed in Table 4. In this system, the load demand is fixed at 2630 MW. Moreover, the loss coefficient *B* matrices are shown in [4].

Table 4. Generation unit data of 15 units system

Unit	P_i^0*(MW)*	P_i^{min}*(MW)*	P_i^{max}*(MW)*	a_i *($)*	b_i*($/MW)*	c_i *($/MW^2)*	UR_i *(MW/h)*	DR_i *(MW/h)*	Prohibited zones *(MW)*
1	400	150	455	671	10.1	0.000299	80	120	-
2	300	150	455	574	10.2	0.000183	80	120	[180, 225] [305, 335] [420, 450]
3	105	20	130	374	8.8	0.001126	130	130	-
4	100	20	130	374	8.8	0.001126	130	130	[180, 200] [305, 335] [390, 420]
5	90	150	470	461	10.4	0.000205	80	120	[230, 255] [365, 395] [430, 455]
6	400	135	460	630	10.1	0.000301	80	120	-
7	350	135	465	548	9.8	0.000364	80	120	-
8	95	60	300	227	11.2	0.000338	65	100	-
9	105	25	162	173	11.2	0.000807	60	100	-
10	110	25	160	175	10.7	0.001203	60	100	-
11	60	20	80	186	10.2	0.003586	80	80	-
12	40	20	80	230	9.9	0.005513	80	80	[30, 40] [55,65]
13	30	25	85	225	13.1	0.000371	80	80	-
14	20	15	55	309	12.1	0.001929	55	55	-
15	20	15	55	323	12.4	0.004447	55	55	-

After simulating this case, the best solutions obtained from all methods that satisfy the system constraints are shown in Table 5. It can be clearly seen that the proposed method has the cheaper solution among the all methods.

In addition, after performing 30 trials, the statistical results of all method are listed in Table 6. The results of Table 6 show that in spite of increasing the size of system, the proposed method is acceptable and truthful.

Table 5. Best solution of six units system

Unit power output	SA [10]	GA [10]	TS [10]	PSO [10]	MTS [10]	**ICA**
P_1 (MW)	453.6646	445.5619	453.5374	454.7167	453.9922	**453.8922**
P_2 (MW)	377.6091	380.0000	371.9761	376.2002	379.7434	**379.8405**
P_3 (MW)	120.3744	129.0605	129.7823	129.5547	130.0000	**129.4512**
P_4 (MW)	126.2668	129.5250	129.3411	129.7083	129.9232	**129.9232**
P_5 (MW)	165.3048	169.9659	169.5950	169.4407	168.0877	**169.0877**
P_6 (MW)	459.2455	458.7544	457.9928	458.8153	460.0000	**459.0051**
P_7 (MW)	422.8619	417.9041	426.8879	427.5733	429.2253	**428.1584**
P_8 (MW)	126.4025	97.8230	95.1680	67.2834	104.3097	**98.3097**
P_9 (MW)	54.4742	54.2933	76.8439	75.2673	35.0358	**42.0358**
P_{10} (MW)	149.0879	144.2214	133.5044	155.5899	155.8829	**155.6362**
P_{11} (MW)	77.9594	77.3002	68.3087	79.9522	79.8994	**79.9023**
P_{12} (MW)	73.9489	77.0371	79.6815	79.8947	79.9037	**80.0000**
P_{13} (MW)	25.0022	31.1537	28.3082	25.2744	25.0220	**25.1891**
P_{14} (MW)	16.0636	15.0233	17.7661	16.7318	15.2586	**15.1567**
P_{15} (MW)	15.0196	33.6125	22.8446	15.1967	15.0796	**15.1298**
Total output (MW)	2663.29	2661.23	2661.53	2661.19	2661.36	**2660.7172**
P_{loss} (MW)	33.2737	31.2363	31.4100	31.1697	31.3523	**30.7549**
Total cost ($/h)	32786.40	32779.81	32762.12	32724.17	32716.87	**32712.34**

Table 6. Comparison of ICA performance with other methods for 15 units system

Methods	Maximum cost ($/h)	Average cost ($/h)	Minimum cost ($/h)	Standard deviation	Average CPU time (s)
SA	33028.95	32869.51	32786.40	112.32	71.25
GA	33041.64	32841.21	32779.81	81.22	48.17
TS	32942.71	32822.84	32762.12	60.59	26.41
PSO	32841.38	32807.45	32724.17	21.24	13.25
MTS	32796.15	32767.21	32716.87	17.51	3.65
ICA	**32794.05**	**32759.87**	**32712.34**	**15.45**	**1.58**

C. Computation efficiency

Table 7 shows the computational time of the proposed method for both case studies. It can be seen that proposed method has enough efficiency for solving ED problem. In addition, Figure 2, shows the convergence characteristic of the proposed method for 15- generating unit system. It can be seen that the proposed method after 9 iterations reaches to the optimum point. The best method among other methods, as shown in [10], it reaches to the optimum point after around 85 iterations. So, the convergence of the proposed method to the optimum solution is faster than the other methods

Table 7. Computational time of the proposed method

	Average CPU time (s)
6- generating unit system	0.58
15-generating unit system	2.21

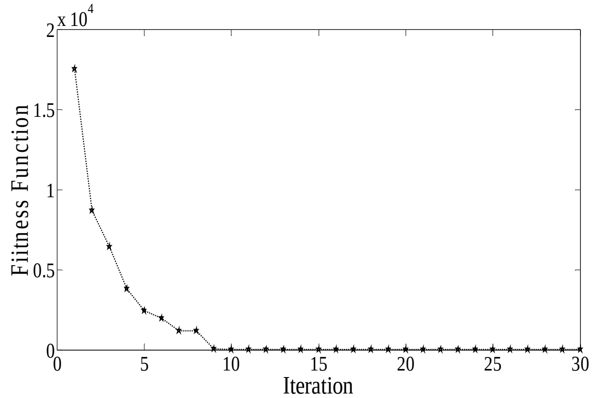

Figure 2. Convergence characteristic of the proposed method

6. Conclusion

In this paper Imperialist Competitive Algorithm (ICA) for solving the Economic Dispatch (ED) problem was presented. Two appropriate strategies for initialization and handling the equality and inequality constraints were utilized which always provide feasible solutions. To show the ability of the proposed method for ED problem, two different test systems are used. Comparing the results of the proposed method with other conventional methods that is listed in [10], it can be derived that the proposed method can find the best solution better than other methods. Moreover, the effectiveness of the proposed method is shown by low computational time and fast convergence.

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