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Dynamic Economic Dispatch with Valve-Point Effect Using Crow Search Algorithm

Cenk Andic, Ali Ozturk and Salih Tosun

Abstract—**This paper presents a method based on meta-heuristic to solve Dynamic Economic Dispatch (DED) problem in a power system. In this paper, Crow Search Algorithm (CSA), which is one of the heuristic methods is proposed to solve the DED problem in a power system. In this study, line losses, generation limit values of generators, generation-consumption balance, valve-point effect and ramp rate limits of generator are included as constraints. The CSA is implemented on two different test cases. Finally, the CSA results are compared with the results of well-known heuristics in the literature such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Symbiotic Organism Search (SOS) algorithm, Artificial Bee Colony (ABC) algorithm, Simulated Annealing (SA), Imperial Competitive Algorithm (ICA), Modified Ant Colony Optimization (MACO) algorithm. The results show that the proposed algorithm has a better operating cost. With the results of the algorithm proposed in the test system 1, a profit of $2,056,5931 per day and $751,751,4815 per year is obtained. It is seen that with the results of the algorithm proposed in the test system 2, a daily profit of $12,279,7328 and a yearly profit of $4,482,102,472 are obtained. Test systems are operated by using less fuel with the results of the proposed algorithm and thus the harmful gas emissions released by thermal production units to the environment are also reduced.**

Index Terms—**Crow search algorithm, dynamic economic dispatch, thermal power units, valve-point effect**

I. Introduction

THE DEMAND for electrical energy is increasing day by day. On the contrary, fossil energy resources are decreasing. Thus, it is an important issue to operate the electrical energy with the least cost [1-3].

Thermal power plants that provide electrical energy production have production costs so the generators are spending fuel. These fuel they spend are modeled with a quadratic equation called fuel cost function. The purpose of the Economic Dispatch (ED) problem is to distribute the power required by the loads on the power systems taking into account the fuel costs of the generators. Thus, more electric power generation is expected from the generator, which has a low fuel cost. However, when performing these loads to the generators, the lower and upper bound of parameters will be taken to produce. The ED problem can be solved by traditional methods [2-19]. A more realistic analysis is made by including the valve-point effect of the generators. In this case, the fuel cost function transforms from a quadratic equation to a non-convex equation [3-6]. In this case, it becomes difficult to find the global best solution to the problem. Therefore, heuristic methods are used to solve this problem, which is a non-convex structure [7-31]. [13] used the method of Artificial Neural Networks (ANN) to solve the ED problem.

In the literature, when we examine the dissolution of this problem by heuristic methods, we see that the ED problem is solved by Genetic Algorithm (GA) in the study of [14]. [15] Solve the ED problem with Particle Swarm Optimization (PSO) algorithm. [16] solves with Artificial Bee Colony (ABC) algorithm. [17] solves the ED problem with Crow Search Algorithm (CSA). [18] has solved the ED problem using Grey Wolf Optimization (GWO) algorithm.

The ED problem aims to distribute the load value given for a only one hour to the generators. However, in operating conditions, the load value changes continuously [11-33]. In this case, the Dynamic Economic Dispatch (DED) problem is solved which takes into account the hourly load change. The load sharing is provided to the generators according to the 24-hour load change [35]. However, the part to be considered here should be paid to the production increase or decrease limits (ramp limit) of generators for hourly load changes [19]. [20] has solved the DED problem using the Symbiotic Organisms Search (SOS) algorithm. [21] has solved the DED problem using Harmony Search Algorithm (HSA). [22] has solved the DED problem using Simulated Annealing (SA) technique.

In this study, the CSA, which is an heuristic methods is proposed to solve the DED problem. The CSA was run on two different test systems. The results obtained were compared with other results in the literature such as the SA [22], the GA [24], the PSO [25], Imperial Competitive Algorithm (ICA) [26], Sequential Quadratic Programming (SQP) [27], the PSO

CENK ANDIC, is with Department of Electrical Engineering University of Istanbul Technical University, Istanbul, Turkey, (e-mail: andic18@itu.edu.tr).
https://orcid.org/0000-0003-1123-899X

ALI OZTURK, is with Department of Electrical-Electronics Engineering University of Duzce, Duzce, Turkey, (e-mail: aliozturk@duzce.edu.tr).
https://orcid.org/0000-0002-3609-3603

SALIH TOSUN, is with Department of Electrical-Electronics Engineering University of Duzce, Duzce, Turkey, (e-mail: salihtosun@duzce.edu.tr).
https://orcid.org/0000-0002-5698-6628

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[28], Evolutionary Programming–Sequential Quadratic Programming (EP-SQP) [29], Particle Swarm Optimization-Bacterial Foraging (PSO-BF) [30], Chaotic Sequence-Differential Evolution (CS-DE) algorithm [31], Artificial Immune System (AIS) [24], the ABC [24], CDBCO [32], the SOS [20], Modified Ant Colony Optimization (MACO) [33], combining Biogeography-Based Optimization with Brain Storm Optimization (BBOSB) [34] and it was seen that the CSA results found best operating conditions in terms of fuel cost.

II. Problem Formulation of DED Problem

A large part of electrical energy production is met by thermal generation units. In order for thermal power plants to produce electrical energy, they need to burn fuel. The power demanded by the loads given for any given hour is shared between the thermal power plants in the power system with the ED problem. It is based on the idea that the thermal generation unit with less fuel cost should produce more electrical energy. In addition, The DED problem allocates the thermal power plants according to the 24-hour (one-day) changing load values. The fuel cost function of m thermal generation units is shown in Eq. (1) below.

$$\min \sum F_i(P_{Gi}) = \sum_{i=1}^{m} (a_i + b_i.P_{Gi} + c_i.P_{Gi}^2) \quad (1)$$

where, P_{Gi}: it is the active power value produced by the ith thermal power plant. a_i, b_i and c_i are the fuel cost function co-efficients of ith thermal power plant. The fuel cost function of the thermal generation units is expressed as a second order function as shown in Eq. (1). However, in reality, valves are used to adjust the output power of steam turbines. If there is an increase in the output power, the valves are activated in order to increase the input power of the plant. However, while the control mechanism trying to achieve this balance tries to maximize efficiency, a ripple occurs in the output power and this effect is called the valve-point effect [16-17]. In this study, valve-point effects of steam turbines are included in the fuel cost function. With the valve-point effect, the DED problem turns into a non-convex problem and becomes a complex problem without a global solution point. The fuel cost function of a thermal power plant with the valve-point effect included is shown in Eq. (2) below.

$$\min \sum F_i(P_{Gi}) = \sum_{i=1}^{m} (a_i + b_i.P_{Gi} + c_i.P_{Gi}^2) + |d_i.\sin(e_i.(P_{Gi}^{min} - P_{Gi}))| \quad (2)$$

where, d_i and e_i are the fuel cost function co-efficients showing the valve-point effect. P_{Gi}^{min} is the minimum limit value that the ith thermal power plant can produce. In this study, the DED problem with valve-point effects is subjected to constraints given as follows:

A. *Demand Constraint*

$$\sum_{i=1}^{N} P_i = P_D + P_L \quad (3)$$

The sum of the power demanded by the loads (P_D) and the lost power (P_L) must be equal to the sum of the power produced by N thermal power plants (P_i). There must be a balance of power. Power loss can be calculated using B-coefficients, given as follows:

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i B_{ij} P_j \quad (4)$$

B. *Real Power Operating Limits*

The active power produced by thermal power plants has a certain minimum-maximum limit range. Thermal power plants should be operated within this limit range.

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \quad (5)$$

C. *Generating Unit Ramp Rate Limits*

$$P_{Gi,t} - P_{Gi,t-1} \le UR_i \quad (6)$$

$$P_{Gi,t-1} - P_{Gi,t} \le DR_i \quad (7)$$

where $P_{Gi,t}$ and $P_{Gi,t-1}$ are power outputs of the ith generating units at time t and $(t-1)$, UR_i and DR_i are up and down ramp-rate limits of ith generating units.

III. Crow Search Algorithm

The CSA is one of the metaheuristic optimization algorithms introduced by Askarzadeh in 2016 [23]. The CSA is inspired by the intelligent behavior of crows and is a population-based optimization algorithm. Crows live in flocks and each crow has a home in its memory. Crows store their excess food in their nests. While one crow takes its excess food to its nest, it is followed by another crow. Two different situations can occur. i) The crow flies to its nest without noticing that it is being followed and steal it once the owner leaves. ii) The crow realizes that it is being followed and flies to a random place to protect the food in its nest. One of these two situations occurs. We can think of each crow in the flock as a solution to an optimization problem. The steps of the crow search algorithm are given below.

(a) Initialize problem and adjustable parameters
(b) Initialize position and memory of crows
(c) Evaluate fitness function
(d) Generate new position
(e) Check the feasibility of new positions
(f) Evaluate fitness function of new positions
(g) Update memory
(h) Check termination criterion

The flowchart of the crow search algorithm is shown in Fig. 1.

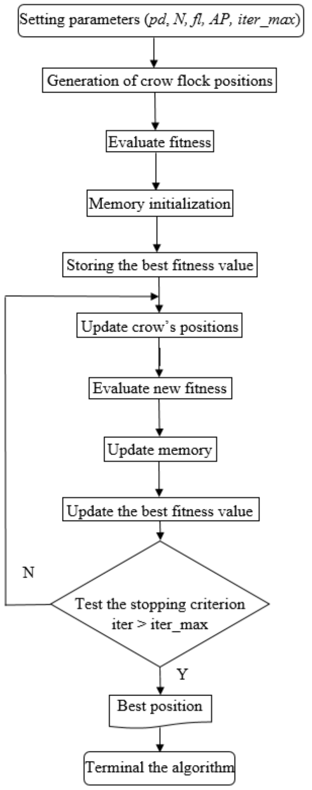

Fig. 1. Flowchart of the proposed method

IV. CSA Implementation For DED Problem

This section shows the steps in implementation the CSA to the DED problem with valve-point effect.

A. Generate The Initial Population of The Flock

In the crow flock population, there are as many crows as the problem size in each flock (flock size is *N*). And each crow represents the solution to the DED problem. For example, since there are five variables in test case 1, the d-dimensional should be five. Initially, the positions of the crows in the flock are randomly generated to fit the lower and upper bounds of the variable in the problem.

$$x^{i,iter} \ (i = 1, 2, \dots, N) \tag{8}$$

$$x^{i,iter} = [x_1^{i,iter}, x_2^{i,iter}, x_3^{i,iter}, \dots, x_d^{i,iter}] \tag{9}$$

B. Calculate The Fitness Value of Flock

The fitness values of each crow in the flock are calculated. Fitness function is shown in Eq. (2).

C. Memory Initialization

In the memory of each crow in the flock there is the location of their nest. Crow's positions represent the solutions to the problem. At first, the locations of the randomly generated crow flock are stored in memory as the best value in the first iteration.

$$m^{i,iter} = [m_1^{i,iter}, m_2^{i,iter}, m_3^{i,iter}, \dots, m_d^{i,iter}] \tag{10}$$

D. Generate A New Positions

As a mentioned, crows follow each other and there are two situations. If crow i notices that crow j is following him, crow i flies to a random place in search space. If crow i does not notice that crow j is following him, crow i flies to his nest. It is the Awareness Probability (AP) that determines which of these two situations will occur. A random number is generated between 0 and 1, and if this number is greater than the AP, the condition occurs that the crow does not notice that it is being followed. The condition that the crow does not notice that it is following is realized. If the randomly generated number is less than the AP, the crow realizes that it is being followed and flies to a random place in the search space.

$$x^{i,iter+1} = \begin{cases} x^{i,iter} + r_i x fl^{i,iter} \text{x} (m^{i,iter} - x^{i,iter}) & r_j \geq AP^{i,iter} \\ a \ random \ position & otherwise \end{cases} \tag{11}$$

where r_j is a random number with uniform distribution between 0 and 1. In the CSA, the parameter of awareness probability is primarily responsible for intensification and diversification (AP). By lowering the awareness probability value, the CSA is more likely to focus its search on a local area where a current good answer can be located.

E. Update Position and Memory

The positions of the crows in the flock change according to the above conditions and are updated in each iteration. Thus, the fitness values of crows also change.

$$x(i,:) = xnew(i,:) \tag{12}$$

In each iteration, a comparison is made between the crows' new fitness value and the best fitness value in memory. If the new fitness value is less than the fitness value in the memory, the fitness value in the memory is updated with the new fitness value.

$$mem(i,:) = xnew(i,:) \tag{13}$$

$$fit\_mem(i) = ft(i) \tag{14}$$

Else, the fitness value in the memory continues to be iterated without updating.

F. Stopping Criterion Testing

Iteration continues until it reaches the maximum number of iterations (*itermax*).

$$iter = 1, 2, 3, \dots, iter_{max} \tag{15}$$

G. The Sample Problem Solution with CSA

The function given in Eq. (2) is taken as a sample problem. The number of problem dimension (variables) is assigned to 3, the flock (population) size is assigned 2, the awareness probability is assigned 0.03, the flight length is assigned 2, while the iteration number of the algorithm is assigned to 10.

At the first step of the algorithm, the crows positions is created randomly. This initial population is given in Table I.

TABLE I
THE INITIAL POPULATION OF CROWS CREATED RANDOMLY AND CALCULATED FITNESS VALUE FOR EACH FLOCK

		Flock1				**Flock2**			
Hour	**Demand**	**Crow1**	**Crow2**	**Crow3**	**Cost**	**Crow1**	**Crow2**	**Crow3**	**Cost**
1	210	161,323	112,687	159,448	2240495	153,838	134,393	115,797	1945802,8
2	200	190,93	140,522	157,873	2899900	151,367	116,055	178,423	2464525
3	190	178,170	84,947	169,862	2435740	178,140	84,182	170,096	2430118
4	185	176,716	149,925	141,714	2839928	164,319	122,589	165,849	2683737
5	190	85,281	102,629	172,330	1707372	184,784	92,273	114,779	2023760,5
6	215	165,579	140,375	170,903	2625049	157,520	76,486	113,896	1333852
7	220	188,945	113,189	122,894	2056104	195,549	96,863	134,994	2079942
8	230	127,142	132,716	164,797	1952345	111,826	133,939	172,949	1892855
9	235	127,624	100,191	137,913	1312305	160,952	85,957	146,416	1588656,5
10	240	178,407	54,306	134,387	1276128	96,930	134,120	110,868	1023892
11	245	77,258	130,910	157,964	1216344	150,175	123,819	148,483	1780530
12	250	190,439	102,133	125,414	1685595	166,093	109,386	136,184	1622263
13	245	194,946	102,271	113,852	1666344	187,306	84,504	159,335	1867377,7
14	255	164,186	93,547	144,415	1476999	165,604	129,499	157,542	1982606
15	260	175,062	123,981	172,951	2126367	167,132	50,729	177,316	1357274
16	255	156,005	144,196	111,942	1577065	182,675	140,968	131,336	2005997
17	250	175,846	101,357	111,813	1395523	152,122	78,995	129,501	1111173,4
18	245	136,916	118,067	173,495	1840623	177,520	149,674	147,016	2298544
19	240	156,562	111,207	160,417	1887705	142,872	78,609	130,964	1129338
20	235	157,574	126,917	120,716	1707607	178,321	108,320	95,977	1481451
21	230	199,419	92,452	88,407	1508064	194,891	117,766	169,552	2528667,2
22	220	125,233	144,511	137,632	1879316	193,117	122,271	90,801	1867484
23	215	178,391	79,761	132,861	1765529	181,223	91,416	132,517	1907126
24	210	181,547	77,373	130,274	1797323	157,890	103,619	131,102	1831493
Total Cost ($/24h)					44,875,770				**44,238,465**

As seen in Table 1, it represents the positions of the crows in the flocks. The positions of the crows also represent the solution to the problem. The fitness value of each flock is calculated according to Eq. (2) for each hour. As a result of the 24-hour dynamic economic dispatch, the least total cost value that gives the best fitness value in the flock is thrown into memory. Thus, the best initial value is stored in memory. The value in memory actually shows the best result up to the current iteration. This is the value for the initial population 44,238,465 $/24h as has been shown in Table 1. Crows store their food in their nests. The positions of the crows indicate the position of their nests. Crows try to reach more food by following each other. By paying attention to the flight length of the crows in the search space, they update the positions of the crows in each iteration. The values of the positions of the crows in the flock in the 9th and 10th iterations are shown in Table 2.

TABLE II
THE CHANGE OF POSITIONS OF THE CROWS ACCORDING TO ITERATIONS

9th Iteration						**10th Iteration**					
Flock1			**Flock2**			**Flock1**			**Flock2**		
Crow1	**Crow2**	**Crow3**	**Crow1**	**Crow2**	**Crow3**	**Crow1**	**Crow2**	**Crow3**	**Crow1**	**Crow2**	**Crow3**
87,647	93,312	92,680	52,864	117,75	71,889	80,797	88,698	87,359	83,244	79,607	78,845
54,232	38,852	63,340	67,064	45,249	154,24	92,930	50,504	82,684	65,052	64,209	60,864
65,378	93,789	96,936	89,324	82,442	137,10	105,582	60,429	86,689	81,497	70,006	73,643
109,60	72,975	148,89	65,606	92,020	106,48	141,102	118,158	67,268	65,243	68,05	125,077
111,99	75,358	78,835	54,752	107,38	122,90	108,314	53,725	89,442	53,051	105,113	120,574
94,387	89,541	63,819	71,060	146,89	58,613	93,239	51,808	53,369	54,072	65,794	103,341
62,609	78,046	146,14	57,173	85,021	66,761	120,953	49,398	74,921	98,117	42,069	75,329
54,478	125,79	77,353	57,374	39,525	110,66	68,335	75,485	61,819	91,004	90,403	68,074
113,21	47,008	59,094	152,10	47,534	60,495	59,497	53,228	126,374	54,929	62,947	124,018
72,229	58,884	154,78	94,087	83,024	78,361	51,442	93,644	135,180	100,56	58,173	72,826
98,341	59,343	108,28	57,386	105,60	101,09	73,722	131,224	58,081	92,015	63,966	97,555
118,85	76,829	75,123	143,49	93,263	76,928	79,056	125,003	45,030	86,437	50,288	116,249
106,97	80,280	79,289	100,20	41,521	89,394	68,079	134,084	55,447	147,812	41,803	51,268
60,971	149,06	68,675	54,333	116,52	109,11	84,899	37,822	149,266	70,649	49,154	154,483
103,18	92,228	70,052	110,13	82,323	92,328	64,736	60,754	129,643	136,239	42,735	102,041
60,383	40,001	167,36	78,708	53,995	126,25	51,915	142,650	65,446	132,819	70,165	52,515
84,088	76,398	91,046	95,703	41,896	106,24	127,86	67,967	53,429	104,513	85,774	54,839
137,16	107,10	60,286	104,61	44,220	49,508	134,457	105,659	49,816	67,041	74,112	67,253
53,534	91,128	121,96	80,327	78,720	93,448	72,620	106,076	80,313	61,134	73,085	103,440
88,644	44,536	110,69	50,367	91,798	46,280	101,658	44,452	96,242	63,734	92,63	96,988
55,556	89,923	115,25	64,914	54,756	126,58	109,763	47,270	87,860	63,202	42,965	133,289
132,40	74,362	64,425	139,09	69,415	55,619	81,113	61,942	108,126	70,144	59,891	105,077
75,531	111,96	89,399	113,21	43,843	122,36	93,289	61,866	95,770	95,136	41,095	138,648
97,956	53,186	53,222	94,969	121,48	63,415	65,137	88,706	58,348	67,446	43,645	127,242
Total Cost ($/24h)		9,449,683			**9,934,455**			6,725,579			**5,261,095**

It can be seen from Table 1 and 2 that the positions of the crows change in each iteration. In each iteration, the crow's positions are updated and the fitness value of the crow flocks is calculated according to these new values. The best fitness value among the flocks is compared with the best value in the memory, and if it is a better value than the value in the memory, the memory value is updated with this new fitness value. This comparison process is performed in each iteration. Table 3 shows the variation of the memory value in each iteration.

TABLE III
THE CHANGE OF THE VALUE IN MEMORY IN EACH ITERATION

Iter_1	**Iter_2**	**Iter_3**	**Iter_4**	**Iter_5**	**Iter_6**	**Iter_7**	**Iter_8**	**Iter_9**	**Iter_10**
44,238,46	36,887,14	30,403,10	26,294,20	22,989,27	19,485,01	16,247,78	12,957,75	9,449,68	5,261,09

At the end of the 10th iteration, the fitness function value is seen as $5,261,09 per day. In this way, the dynamic economic dispatch problem is solved by using the crow search algorithm.

V. SIMULATION RESULTS

In this study, the CSA was used to solve the DED problem. The DED problem includes some constraints such as line losses, ramp-rate limits, valve-point effects and power balance. Thus, the DED problem become a non-convex problem. The proposed algorithm has been tested on two different test systems which are five units with loss and ten units without loss. Simulations were done using a 2.50 GHz Windows 10 personal computer with 16 GB-RAM and MATLAB program package and the CSA was run at least 30 times for two test cases. The results obtained from the CSA were compared with the results of other previously reported methods in the literature. Test cases and results have been given subsections. The parameters of the CSA used in this study are given in Table 4.

TABLE IV
SETTING PARAMETERS OF THE CSA FOR THE DED PROBLEM

Test Cases	pd (Problem Dimension)	AP (Awareness Probability)	fl (Flight Lenght)	Flock_size	Iter_max
Test Case 1	5	0.3	2	30	3000
Test Case 2	10	0.3	2	40	3000

A. *Test Case 1*

There are five thermal generation units in the test case 1. In this case, losses are taken into account and the B co-efficient is given in Table 5.

TABLE V
TRANSMISSION LOSS CO-EFFICIENTS FOR FIVE-UNIT TEST SYSTEM [22]

$$B = \begin{bmatrix} 0.000049 & 0.000014 & 0.000015 & 0.000015 & 0.000020 \\ 0.000014 & 0.000045 & 0.000016 & 0.000020 & 0.000018 \\ 0.000015 & 0.000016 & 0.000039 & 0.000010 & 0.000012 \\ 0.000015 & 0.000020 & 0.000010 & 0.000040 & 0.000014 \\ 0.000020 & 0.000018 & 0.000012 & 0.000014 & 0.000035 \end{bmatrix}$$

System data for five thermal units is given in Table 6.

TABLE VI
SYSTEM PARAMETERS FOR FIVE-UNIT TEST SYSTEM [20]

Parameters	P_1	P_2	P_3	P_4	P_5
a_i ($/h)	25	60	100	120	40
b_i ($/MWh)	2.0	1.8	2.1	2.0	1.8
c_i ($/(MW)^{2}h)	0.0080	0.0030	0.0012	0.0010	0.0015
d_i ($/h)	100	140	160	180	200
e_i (1/MW)	0.042	0.040	0.038	0.037	0.035
$P_{i\,min}$ (MW)	10	20	30	40	50
$P_{i\,max}$ (MW)	75	125	175	250	300
UR (MW/h)	30	30	40	50	50
DR (MW/h)	30	30	40	50	50

The 24-hour changing load data for solving the DED problem on test case 1 are given in Table 7.

TABLE VII
24-HOUR LOAD CHANGE DATA FOR FIVE-UNIT TEST SYSTEM [20]

Hour (h)	Load (MW)	Hour (h)	Load (MW)	Hour (h)	Load (MW)	Hour (h)	Load (MW)
1	410	7	626	13	704	19	654
2	435	8	654	14	690	20	704
3	475	9	690	15	654	21	680
4	530	10	704	16	580	22	605
5	558	11	720	17	558	23	527
6	608	12	740	18	608	24	463

The results show a total operating cost of 41,030.9994 $/24h. In Table 8, the results (minimum, average and maximum value) of the CSA are compared with other results in the previously reported literature and it is seen that the proposed algorithm gives the best result.

TABLE VIII
FUEL COST VALUES FOR TEST CASE 1

Method	Min. ($/24h)	Average ($/24h)	Max. ($/24h)
SA [22]	47,356.0000	-	-
GA [24]	44,862.4200	44,921.7600	45,893.9500
PSO [25]	44,253.2400	45,657.0600	46,402.5200
ABC [25]	44,045.8300	44,064.7300	44,218.6400
ICA [26]	43,117.0500	43,144.4700	43,302.2300
SOS [20]	43,090.5925	43,103.0828	43,162.2146
CSA	41,030.9994	41,079.5397	41,103.6947

TABLE IX
RESULTS FROM THE CROW SEARCH ALGORITHM FOR TEST CASE 2

Hour	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)	P5 (MW)	P6 (MW)	P7 (MW)	P8 (MW)	P9 (MW)	P10 (MW)	Cost ($/h)
1	153.5076	235.6846	81.6252	60.1069	88.9610	159.9993	129.7902	51.2789	20.0463	55	28.1963
2	174.1104	220.5821	158.5912	60.0262	84.7006	159.9844	129.9999	47.0064	20.0004	55	29.7468
3	207.0047	272.3180	227.2118	60.0006	78.8044	159.9958	129.6627	47.0054	21.0429	55	32.9361
4	224.8680	338.2997	295.7740	60.0042	73.0179	159.9943	129.6720	48.0839	21.2884	55	36.1262
5	194.4103	368.0764	339.9999	60.0000	102.9533	159.9999	129.9999	49.3601	20.2221	55	37.7134
6	273.1290	416.5603	339.9959	70.9246	114.2374	157.6254	129.9905	50.5381	20.0004	55	40.9957
7	348.4823	421.9858	339.9998	62.5551	119.1232	158.0220	129.9992	47.0290	20.0021	55	42.6297
8	413.1924	459.9158	339.2464	62.0455	85.2900	159.9999	129.9999	51.2597	20.0501	55	44.2668
9	469.6148	459.9999	339.9999	75.3451	131.9493	159.9999	129.9999	79.5731	22.5176	55	47.6461
10	469.7190	459.4386	339.3061	124.9983	180.6288	159.9999	129.9758	106.6304	46.3029	55	51.2269
11	469.4233	459.9995	339.9998	122.7567	227.7601	154.6573	129.9998	92.4028	20.0005	55	51.0756
12	468.3962	459.8852	339.9926	169.0843	242.7376	159.9998	129.9989	119.9861	34.9188	55	53.6800
13	449.4786	459.7576	339.9988	141.0363	223.0026	159.9983	129.9988	89.0004	24.7282	55	51.0958
14	408.6655	446.9922	339.2466	91.0022	211.2103	159.8815	129.9997	59.0053	22.9962	55	47.6328
15	355.1128	442.8886	329.4883	73.0002	163.7124	159.9999	129.3275	47.4679	20.0021	55	44.2889
16	275.0022	362.0988	289.7085	66.7447	146.8688	159.9909	129.9944	48.1494	20.4419	55	39.4097
17	195.0020	333.8780	321.4467	60.0063	159.5385	159.9194	128.2062	47.0001	20.0027	55	37.7423
18	203.1714	399.4876	339.9952	63.9597	208.0304	159.9653	129.9993	47.0211	21.3697	55	40.9917
19	282.9999	454.4229	339.7089	76.5863	209.1755	159.9995	129.5644	48.5425	20.0002	55	44.2861
20	361.9901	459.5435	339.9986	117.1854	242.9992	159.5332	129.9970	77.9877	27.7651	55	48.8086
21	399.9707	459.9998	338.1435	68.2714	242.9999	159.9249	129.9999	48.3217	21.3680	55	47.5604
22	323.2210	391.9479	265.8824	61.5723	192.0673	150.8171	120.3835	47.1076	20.0006	55	41.1339
23	248.1792	311.0990	185.8063	60.0043	122.1070	159.9983	112.7484	54.7652	22.2921	55	34.6970
24	168.0059	257.7098	167.4774	60.0001	16.6554	159.9993	129.9676	49.1781	20.0063	55	31.3638
									Total Cost ($/24h)		**1,005,250.6**

B. *Test Case 2*

There are ten thermal generation units in the test case 2. In this case, the DED problem was considered without a transmission losses. System data for ten thermal units is given in Table 10.

TABLE X
SYSTEMS PARAMETERS FOR TEN-UNIT TEST SYSTEM [32]

Parameters	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}
a_i ($/h)	958.2	1313.6	604.97	471.6	480.29	601.75	502.7	639.4	455.6	692.4
b_i ($/MWh)	21.6	21.05	20.81	23.9	21.62	17.87	16.51	23.23	19.58	22.54
c_i ($/(MW)^{2}h)	.00043	.00063	.00039	.0007	.00079	.00056	.00211	.0048	.10908	.00951
d_i ($/h)	450	600	320	260	280	310	300	340	270	380
e_i (1/MW)	.041	.036	.028	.052	.063	.048	.086	.082	.098	.094
$P_{i\,min}$ (MW)	150	135	73	60	73	57	20	47	20	55
$P_{i\,max}$ (MW)	470	460	340	300	243	160	130	120	80	55
UR (MW/h)	80	80	80	50	50	50	30	30	30	30
DR (MW/h)	80	80	80	50	50	50	30	30	30	30

The 24-hour changing load data for solving the DED problem on test case 2 are given in Table 11.

TABLE XI
24-HOUR LOAD CHANGE DATA FOR TEN-UNIT TEST SYSTEM [20]

Hour (h)	Load (MW)	Hour (h)	Load (MW)	Hour (h)	Load (MW)	Hour (h)	Load (MW)
1	1036	7	1702	13	2072	19	1776
2	1110	8	1776	14	1924	20	2072
3	1258	9	1924	15	1776	21	1924
4	1406	10	2072	16	1554	22	1628
5	1480	11	2146	17	1480	23	1332
6	1628	12	2220	18	1628	24	1184

The operating value results of the generators are shown in Table 9. The results show a total operating cost of 1,005.250.6 $/24h. In Table 12, the results (min., average and max.) of the CSA are compared with other results in the previously reported literature and it is seen that proposed algorithm gives the best result.

TABLE XII
FUEL COST VALUES FOR TEST CASE 2

Method	Min ($/24h)	Average ($/24h)	Max ($/24h)
SQP [27]	1,051,163.0000	-	-
PSO [28]	1,036,506.0000	1,040,496.0000	-
EP-SQP [29]	1,034,100.0000	-	-
PSO-BF [30]	1,026,537.2600	1,028,826.7400	1,033,565.2700
CS-DE [31]	1,023,432.0000	1,026,475.0000	1,027,634.0000
AIS [24]	1,021,980.0000	1,023,156.0000	1,024,973.0000
ABC [24]	1,021,576.0000	1,022,686.0000	1,024,316.0000
CDBCO [32]	1,021,500.0000	1,024,300.0000	-
SOS [20]	1,020,894.0757	1,021,072.6846	1,021,194.9972
MACO [33]	1,019,093.1700	1,019,254.2100	1,024,310.8000
BBOSB [34]	1,017,530.3328	1,018,487.8504	1,031,843.5673
CSA	1,005,250.6000	1,007,546.0000	1,009,304.0000

VI. CONCLUSION

The minimum fuel cost and operating conditions of a power system are found by the economic dispatch problem. However, for a more realistic analysis, this problem should be solved by considering the 24-hour load change. While making hourly load sharing of generators, ramp rate limits were taken into consideration. With the proposed algorithm, the DED problem was solved on two different test systems specified in the literature. The CSA results show that it is operated with the lowest fuel cost in the conditions determined in the test case 1. With the results of the CSA, the test system 1 is operated at a cost of $41,030,9994 per day. With the results of the SOS algorithm, which is the best result in the literature, the test system 1 is operated at a cost of $43,090,5925 per day. With the proposed algorithm, a daily profit of $2,059.5931 is obtained. The CSA results show the operation of the system with the lowest fuel cost under the conditions specified in the initial test system (including losses). In the test case 2, the number of thermal generation units increases, but the losses are neglected. In this test system, the CSA found the lowest operating conditions (min., average and max.). The results of the CSA show that test system 2 is operated at a cost of $1,005,250,6000 per day. With the results of the BBOSB algorithm, which is the best result in the literature, this system is operated with a daily cost of $1,017,530,3328. With the proposed algorithm, a daily profit of $12,279.7328 is obtained. The results show that the CSA gives better results than other algorithms mentioned in the literature. By using the CSA, a yearly profit of $751,751.4815 and $4,482,102.472 are provided in test system 1 and 2, respectively.

With the CSA algorithm, multi-objective DED problems can also be successfully solved, for example environment emission dispatch and including photovoltaic (PV) and energy storage systems and electric vehicles (EV).

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BIOGRAPHIES

CENK ANDIC received the B.S. degrees in electrical-electronics engineering from the University of Duzce, Turkey in 2018 where he is currently pursuing the Ph.D. degree in electrical-electronics engineering. He has been an Research Assistant with the Electrical Engineering Department, Istanbul Technical University (ITU). His research interests include economic dispatch and power system, state estimation and renewable energy.

ALI OZTURK received his B.S. in Electrical Engineering Yildiz Technical University, Turkey, in 1996, his M.Sc. in Electrical Engineering from Sakarya University, Sakarya, Turkey, in 2001 and his Ph.D. in 2007 from the same university. His research interests include voltage stability and optimization in electric power systems.

SALIH TOSUN received his B.S. in Electrical Education Marmara University, Turkey, in 1986, his M.Sc. in Electrical Engineering from Marmara University, Istanbul, Turkey, in 1991. His research interests include voltage stability and optimization in electric power systems.