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Applications of Particle Swarm Optimization Algorithm to Solving the Economic Load Dispatch of Units in Power Systems with Valve-Point Effects

Hossein Shahinzadeh[1], Sayed Mohsen Nasr-Azadani[2], Nazereh Jannesari[3]
[1,2]Department of Electrical Engineeing, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran
[3]Department of Engineering, SepahanInstitueof Higher Education, Isfahan, Iran

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ABSTRACT

Reduction of operating costs in power system in order to return the investment costs and more profitability has vital importance in power industry. Economic Load Dispatch (ELD) is one of the most important issues in reducing operating costs. ELD is formulated as a nonlinear optimization problem with continuous variables within the power plants. The main purpose of this problem is optimal planning of power generation in power plants with minimum cost by total units, regarded to equality and inequality constraints including load demand and the range of units' power productivity. In this article, Economic Load Dispatch problem has been modeled by considering the valve-point loading effects with power plants' constraints such as: the balance of production and consumption in system, the forbidden zones, range of production, increasing and decreasing rates, reliability constraints and network security. To solve the problem, Particle Swarm Optimization (PSO) Algorithms has been employed. To evaluate the effectiveness of the proposed method, the problem has been implemented on a power system with 15 generating units and the results have been evaluated.

Corresponding Author:

Hossein Shahinzadeh,
IEEE Member, Department of Electrical Engineeing,
Amirkabir University of Technology, Tehran, Iran.
Email: H.S.Shahinzadeh@ieee.org, Shahinzadeh@aut.ac.ir.

1. INTRODUCTION

Most of optimization problems in power systems are Economic Load Dispatch (ELD) with complicated and nonlinear characteristics, equality and inequality constraints, that makes them difficult to solve mathematically. ELD is one of the main issues in terms of management and operation of the power system that its purpose was to determine the production rate per unit power plant in a way that system's load is provided with the minimum cost, while all constraints are respected.ELD has been complicated by the enlargement of power systems and it became difficult to find the best of many local optimum points.

In general, the methods proposed to solve ELD, can be divided into two categories, the classic methods and the smart methods. Gradient method, λ repetition, nonlinear programming, and dynamic programming are the first methods proposed to solve the Economic Load Dispatch problem; however these methods would not be useful when the cost functions are nonlinear. So in some cases, it will be very difficult to achieve optimal solutions. For this reason, in recent years, the smart algorithms have been used for heuristic optimization methods to overcome this problem. Therefore in recent years, different smart and innovative algorithms such as: Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Evolutionary Programming Algorithm (EP), Gravitational Search Algorithm (GSA), … have been proposed to solve this problem.

In reference [1-2] of the classic method, Lagrange multiplier based on nonlinear programming has been used to solve ELD issue. In references [3-5], types of classic algorithms and developed particle swarms have been used to solve the problem. In references [6-14], other types of smart algorithms such as the genetic algorithm and modification of its extended version, evolutionary programming algorithm, differential evolution, gravitational search algorithm and hybrid algorithms have been used to solve the Economic Load Dispatch problem.

In this article, particle swarm optimization (PSO) algorithm has been used to solve the Economic Load Dispatch problem. To solve more realistic model of ELD issue, the effect of the steam inlet valve has been considered in the cost functions related to the power plants' fuel. Finally, in order to show the efficiency of the proposed algorithm, a power system with 15 generating units and its results have been evaluated.

2. FORMULATION OF THE ECONOMIC LOAD DISPATCH PROBLEM

2.1. The Cost Function by Considering the Valve-Point Effects

The ELD determines a method with the most efficiency, the lowest cost and the reliable operation of a power system with proper Dispatch of energy generating sources to supply the system's load. Its primary purpose is to minimize the total cost of production with regard to operational limitations of generating resources. The ELD issue determines the amount of load for power plants in order to reduce the costs. Its formulation is implemented as an optimization problem to minimize the total cost of fuel of power plants which provide load and loss. So the ELD issue can be expressed with the following objective function:

$$\min \sum_{i=1}^{N} F_i\left(P_i\right) + K_l \left(\sum_{i=1}^{N} P_i - P_D - P_{Loss} \right)^2 \tag{1}$$

In the above equation:

$F_i\left(P_i\right)$: is fuel cost of the i_{th} power plant,

N : is number of generators operating system,

P_i: is output power of the i_{th} generator;

P_D : is load demand;

P_{Loss} : is transmission network's loss.

$F_i\left(P_i\right)$: as a quadratic equation can be expressed as follows:

$$F_i\left(P_i\right) = a_i + b_i P_i + c_i P_i^2 \tag{2}$$

In equation (2), a_i, b_i and c_i are cost coefficients of the i_{th} generator. To consider the valve-point effects, sine functions get into the objective function as follows:

$$F_i\left(P_i\right) = a_i + b_i P_i + c_i P_i^2 + \left| e_i \, Sin\left(h_i \left(P_i^{\min} - P_i\right)\right)\right| \tag{3}$$

That in the above equation, e_i and h_i are coefficients corresponding to the position of the i_{th} generator's steam valves, the cost function of equation (1) changes into a non-convex and polynomial composite function. Figure 1 shows the valve-point effects on the nonlinearity of the cost function. In addition to the effects of valve's position, any other costs such as maintenance costs or pollution can be added to the cost function. The obtained objective function subject to the following limitations would result the formulation of the ELD issue.

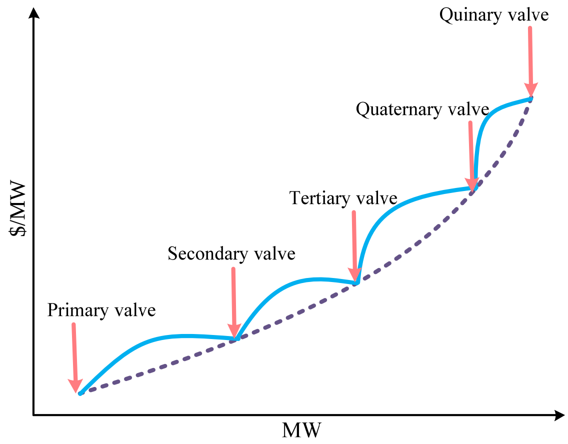

Figure 1. The valve-point effects on the cost function of power plant unit.

2.2. Issue Bonds:

2.2.1. The Balance of Production and Consumption of Power in the System

The total power generated by all units in the circuit must be equal to the total consumption of the system.

$$\sum_{i=1}^{N} P_i - P_D - P_{Loss} = 0 \tag{4}$$

Transmission network's loss (P_{Loss}) depends on the physical structure of the network and the rate of production, and is calculated by using load flow calculations or B loss coefficients with the following formula:

$$P_{Loss} = \sum_{i=1}^{N}\sum_{j=1}^{N} B_{ij} P_i P_j + \sum_{i=1}^{N} B_{0i} P_i + B_{0,0} \tag{5}$$

That in the above equation, $B_{i,j}$ is i_{th}, j_{th} loss element of a loss square matrix, $B_{0,i}$ is the i_{th} loss vector and $B_{0,0}$ is the loss constant.

2.2.2. Power Generation Limitations

The output power of each generator must not be higher than the nominal and it should not be less than the amount which is necessary for the stable operation of the boiler. Thus, the production is so limited to be between predetermined minimum and maximum range. Each productivity unit with an estimated production can be expressed by the following equation in the circuit:

$$P_i^{\min} \le P_i \le P_i^{\max} \tag{6}$$

Above estimations, in addition to being caused by technical constraints of per unit, will lead that the unit with lower cost does not produce more than its maximum allowable power and the unit with more cost does not produce lower than its allowable power.

2.2.3. Limitation of Increasing and Decreasing Rate of Power Generation

For technical reasons, thermal power plants cannot increase or decrease their power immediately and this gain or loss is associated with a pause. In this way, each power plant has limitations in gradient of increasing or decreasing of its productivity power that violation of these restrictions will result in damage to the rotor and it causes more operation costs, that these constraints are expressed by the following relations:

$$\begin{cases} P_i^{\min}(t) \le P_i(t) \le P_i^{\max}(t) \\ P_i^{\min}(t) = \max\left(P_i(t-1) - RDR_i \ , \ P_i^{\min}\right) \\ P_i^{\max}(t) = \min\left(P_i(t-1) + RUR_i \ , \ P_i^{\max}\right) \end{cases} \tag{7}$$

In above equation, RDR_i is the reduced rate of plant's power generation and RUR_i is the increased rate of plant's power generation. In order to enforce these constraints, it is necessary to ascertain the status of primary production of per power plant.

2.2.4. Environmental Costs

Reduction of air pollution is certainly one of the most important challenges facing humanity now and in the coming decades. Electricity generated from fossil fuels, spreads several different substances such as sulfur dioxide, nitrogen oxide and carbon dioxide in the air. Two most important samples of these compounds that produced in the most power plants are Nitrogen Oxide (NO_X) and sulfur dioxide (SO_X). In this article, the costs caused by the spreading prevention of these compounds in the air, have been considered in the objective function.

Diffusion equation is considered as a quadratic function with constant coefficients for each unit. The total diffusion cost is used as the objective function (cost function) to be minimized. Of course, the g factor is considered as a price error factor. g factor's unit is $\$/KG$ and converts the diffusion function to the cost function:

$$F_{obj} = \sum_{i=1}^{n} C_i\left(P_i\right) + \sum_{i=1}^{n} E_i\left(P_i\right) \tag{8}$$

2.2.5. Forbidden zones

For technical reasons, plants cannot produce power in some areas between the minimum and maximum of their own production. These areas named as forbidden zones and defined as $[P_{i,jL} - P_{i,jU}]$. So the possible task areas of the i_{th} production unit are specified according to equation 9:

$$\begin{cases} P_i^{\min} \le P_i \le P_{i,1}^{L} \\ P_{i,\mathrm{j}-1}^{U} \le P_i \le P_{i,\mathrm{j}}^{L} \qquad , \ \mathrm{j} = 2,3, \ \dots \ , z_i \\ P_{i,z_i}^{U} \le P_i \le P_i^{\max} \end{cases} \tag{9}$$

That z_i is the number of forbidden zones of the i_{th} unit.

2.2.6. Reliability Constraints and Network Security

Other constraints due to standards of reliability and network security can also be considered as technical constraints of ELD issue. In most cases, these limitations are considered in other studies or planning and ELD is resolved without consideration of these constraints.

3. PARTICLE SWARM OPTIMIZATION ALGORITHM (PSO)

For the first time, Kennedy and Aybrhart, introduced particle swarm optimization algorithm as a new method in 1995 [15]. The main purpose of their research was to simulate the social behavior of flock and fish. By developing their research, they discovered that the model of these groups' members' social behavior can also act as a powerful optimization method with some modifications. The first version of this method was just used to solve nonlinear continuous optimization problems. However, many advances in order to develop this field, have upgraded its abilities to solve a large range of complex optimization problems in science and engineering.

The key and attractive aspect of PSO is its simplicity, so that it only has two models of equation. In this method, each particle's coordinates represent a possible answer associated with two vectors, position (X_i) and velocity (V_i) vectors, in the N-dimensional search space include:

$X_i = [X_{i1}, X_{i2}, \dots, X_{iN}]$ That $X_{i,n}^k \in [l_n, u_n], 1 \le n \le N$ such that u_n and l_n are respectively the upper limit and lower limit for the n_{th} dimension and $V_i = [V_{i1}, V_{i2}, \dots, V_{iN}]$, that is limited by a velocity vector $V_{max}^k = (V_{max,1}^k, \dots, V_{max,n}^k, \dots, V_{max,N}^k)$, that two vectors are dependent and associated with each particle i. An assembly of particles has been made from number of particles (possible answers) that progress to find optimal answers in a space of possible answers. Position of each particle based on its best search, and the best overall experience of group flight and previous velocity vector of the particle itself, is according to the following model. In figure 2, the particles moving interaction has been shown by the following equations:

$$v_i^{k+1} = wv_i^k + c_1r_1(pbest_i^k - x_i^k) + c_2r_2(gbest^k - x_i^k) \quad (10)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (11)$$

In which:

c_1 and c_2 are two positive constants which known as acceleration coefficients.

r_1 and r_2 are two random numbers in the range [0,1].

w is the inertia weight that linearly decreases from 0.9 to 0.4 during the process.

$pbest_i^k$ is the best position of particle i that obtained based on particle's experience.

$$\mathrm{Pbest}_i^k = [x_{i1}^{pbest}, x_{i2}^{pbest}, \dots, x_{iN}^{pbest}] \quad (12)$$

$gbest^k$ is the best position of the particle based on group experience.

$$gbest = [x_1^{gbest}, x_2^{gbest}, \dots, x_N^{gbest}] \quad (13)$$

K is frequency indicator.

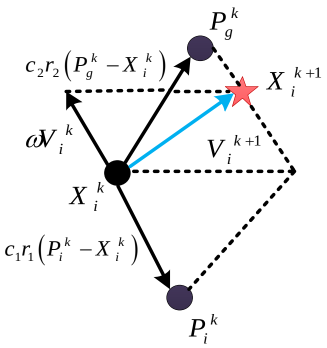

Figure 2. Particles' moving interaction in the PSO algorithm

Some of the advantages of PSO in comparison with other similar optimization methods are:

- This method does not need differentiation unlike many traditional methods.
- It has flexibility to integrate with other optimization techniques in order to develop complex tools.
- It has less sensitivity to the objective function's nature, which means it has convexity or continuity.
- Unlike many other evolutionary computational methods, it needs fewer parameter settings.
- It has the ability to escape from local minimum.
- It can easily be implemented and planned with basic mathematical and logical operations.
- It can be used for the objective functions with random nature. Similar to the case that one of the optimization variables is random.
- It does not need a proper initial response to start the frequency process.
- *PSO algorithm advantages in comparison with the genetic algorithm (GA) :*

As one of the evolutionary computational methods, PSO, similar to genetic algorithm (GA) is started from series of initial population as random responses and develops the process of searching through a repetition process. By the development and application of PSO algorithm in recent years, researchers concluded that PSO algorithm can be used to solve similar problems in GA. From the standpoint of practical cases, advantages of PSO are summarized as follows.

In addition to traditional optimization algorithms based on gradient, there are many other innovative methods that compete with PSO such as Genetic Algorithm, evolutionary programming and more recently Ant Optimization Algorithm. Generally, as most of these methods which used to solve different optimization problems, the above method is also able to solve different optimization issues. However, some of these competing methods, have some deficiencies and weak points such as following cases:

- They need more parameter settings.
- Above methods need too computational time.
- Development and modification of the above algorithms needs many programming skills, in order to adapt them to different kinds of optimization problems.

Some of these techniques need to convert to binary field instead of working with the actual values of variables' system. In spite of simple concept and easy implementation of presented method, its superiority in many different applicatory fields has been proved in comparison with other methods.

4. NUMERICAL STUDY AND RESULTS' ANALYSIS

In this section, the proposed algorithm has been implemented on a power system with 15 generating units, which has been studied in several papers. All information has been given in tables 1 and 2 for simulation of the desired test network. Also the applicative power at different times has been given in table 3.

Table 1. Characteristics of the units with regard to pollution coefficients.

Unit	a_i	b_i	c_i	e_i	h_i	α_i	β_i	γ_i	$P_{i,min}$(MW)	$P_{i,max}$(MW)
1	671	10.1	0.0002	357.9572	0.0310	77.303	5.763	0.09	150	455
2	574	10.2	0.0002	306.2107	0.0510	50	- 5.48	0.093	150	455
3	374	8.8	0.0011	199.5171	0.0910	57.254	- 5.46	0.054	20	130
4	374	8.8	0.0011	199.5171	0.0912	57.254	- 5.43	0.054	20	130
5	461	10.4	0.0002	245.9288	0.0812	60.5	- 5.93	0.064	150	470
6	630	10.1	0.0003	336.085	0.0612	75	- 5.43	0.094	135	460
7	548	9.8	0.0004	292.3406	0.0512	65	- 5.43	0.089	135	465
8	227	11.2	0.0003	121.0973	0.342	62	- 4.43	0.044	60	300
9	173	11.2	0.0008	92.29	0.552	58.7	- 4.02	0.041	25	162
10	175	10.7	0.0012	93.35693	0.53	57	- 4.02	0.041	20	160
11	186	10.2	0.0036	99.22508	0.43	69	- 4.1	0.042	20	80
12	230	9.9	0.0055	122.6977	0.33	69.5	- 5.2	0.045	20	80
13	225	13.1	0.0004	120.0303	0.23	69	- 5.2	0.045	25	85
14	309	12.1	0.0019	164.8417	0.143	55	- 5.43	0.051	15	55
15	323	12.4	0.0044	172.3102	0.13	57.84	- 5.43	0.054	15	55

Table 2. Characteristics of the gradient's rate of system's 15 units.

Unit	UR_i(MW)	DR_i(MW)	P_{io}(MW)
1	80	120	400
2	80	120	300
3	130	130	105
4	130	130	100
5	80	120	90
6	80	120	400
7	80	120	350
8	65	100	95
9	60	100	105
10	60	100	110
11	80	80	60
12	80	80	40
13	80	80	30
14	55	55	20
15	55	55	20

Table 3. The amount of required consumption power in a 24-hour period.

Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Demand (MW)	1898	1972	2120	2268	2342	2490	2564	2638	2786	2934	3008	3082

Hour	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Demand (MW)	2934	2786	2638	2416	2342	2490	2638	2934	2786	2490	2194	2046

In this paper, 2010 *Matlab*software has been used to code genetic algorithm in order to simulate the ELD issue among power plants considering the valve-point loading effects and practical constraints of power system.

5. THE RESULTS OF SIMULATION WITH THE PROPOSED ALGORITHM

For this system, the number of particles and repetitions has been selected equal to 100 for each of populations. The results of the proposed algorithm's performance on this system have been presented in table 4. We see that, the results obtained from particle swarm optimization algorithm for this system requires less time than the other methods. The proposed algorithm has been also reached to an absolute optimal answer for every 100 times of different performances at the least frequency, which indicates high-power of proposed algorithm to achieve the absolute optimal answer and optimization of ELD issue. Figure 3 has graphically shown load's dispatch accomplished by proposed algorithm in 24-hours based on units' generating power.

Table 4. Results for the proposed Load's Dispatch by using PSO algorithm on 15 units' system.

Unit	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	162.85	365.76	350.51	337.36	304.25	271.72	265.59	256.97	152.15	275.24	251.38	162.85
2	454.84	395.98	347.91	391.61	340.49	270.66	273.31	257.22	305.84	220.39	246.81	454.84
3	108.76	124.34	89.81	125.59	125.49	118.83	121.85	125.30	124.21	127.32	126.26	108.76
4	109.87	125.58	122.71	126.37	125.54	118.93	121.28	127.21	124.25	124.17	126.21	109.87
5	155.10	365.62	382.70	389.21	304.53	270.54	305.09	273.01	305.69	218.46	151.76	155.10
6	145.20	389.90	438.55	335.84	339.75	339.81	276.78	340.87	229.00	242.88	188.50	145.20
7	144.21	370.37	349.04	327.49	303.47	383.57	268.63	254.49	229.56	256.17	191.02	144.21
8	162.24	296.88	293.68	298.76	297.57	271.27	287.19	255.65	229.17	218.11	188.69	162.24
9	140.42	157.83	155.92	104.73	156.54	150.06	155.72	127.51	155.88	159.32	157.00	140.42
10	138.42	155.92	152.75	156.07	156.54	148.77	156.79	156.76	156.32	157.40	156.28	138.42
11	58.76	74.78	73.97	78.31	75.57	67.81	78.44	77.80	74.63	78.32	76.27	58.76
12	58.72	76.92	73.90	76.98	75.54	68.01	76.95	77.62	76.71	39.84	75.89	58.72
13	65.02	80.85	78.93	80.93	79.58	72.05	81.52	81.88	79.30	82.05	81.32	65.02
14	33.76	50.82	48.84	53.15	50.79	43.02	52.06	38.62	49.84	52.32	51.26	33.76
15	33.76	50.38	48.69	51.52	50.29	42.88	42.70	39.02	49.39	15.92	51.27	33.76

Unit	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
1	262.97	454.51	257.10	352.64	334.16	453.03	248.46	263.76	248.20	273.22	317.88	344.69
2	185.86	193.79	256.55	304.93	335.50	268.51	391.02	273.13	234.01	272.89	309.54	340.23
3	124.08	112.53	124.02	125.87	124.44	114.65	120.34	124.01	118.68	117.99	126.59	128.96
4	123.18	112.57	126.97	123.90	123.50	113.27	121.35	123.58	115.58	118.01	122.86	129.42
5	187.11	193.75	265.71	304.49	336.18	270.84	261.20	229.01	266.39	275.19	308.71	346.32
6	186.85	190.11	269.68	318.26	391.12	268.99	392.25	233.71	234.28	443.50	308.66	340.43
7	171.47	191.42	271.50	315.92	346.69	310.11	255.14	229.85	378.67	270.69	323.28	339.47
8	172.07	189.41	289.25	296.86	295.31	270.71	106.96	225.47	236.75	271.13	299.93	298.98
9	155.95	144.53	161.44	156.23	157.06	147.56	151.26	155.71	150.22	150.01	161.93	161.52
10	152.82	143.60	150.45	155.23	155.58	145.65	150.42	156.18	144.47	147.31	159.94	159.25
11	73.38	62.56	78.32	74.82	77.18	63.55	69.62	75.72	67.41	71.01	78.93	78.42
12	74.08	62.55	78.31	76.34	74.52	66.65	67.55	77.20	67.11	67.48	79.93	77.57
13	77.90	67.49	68.50	79.69	80.27	68.13	75.27	79.67	70.076	74.01	84.93	79.32
14	49.10	37.53	53.61	50.47	52.03	38.65	39.93	49.57	42.12	42.91	54.94	54.42
15	49.09	37.57	38.51	50.28	50.40	37.64	39.16	45.36	41.96	42.62	47.86	54.92

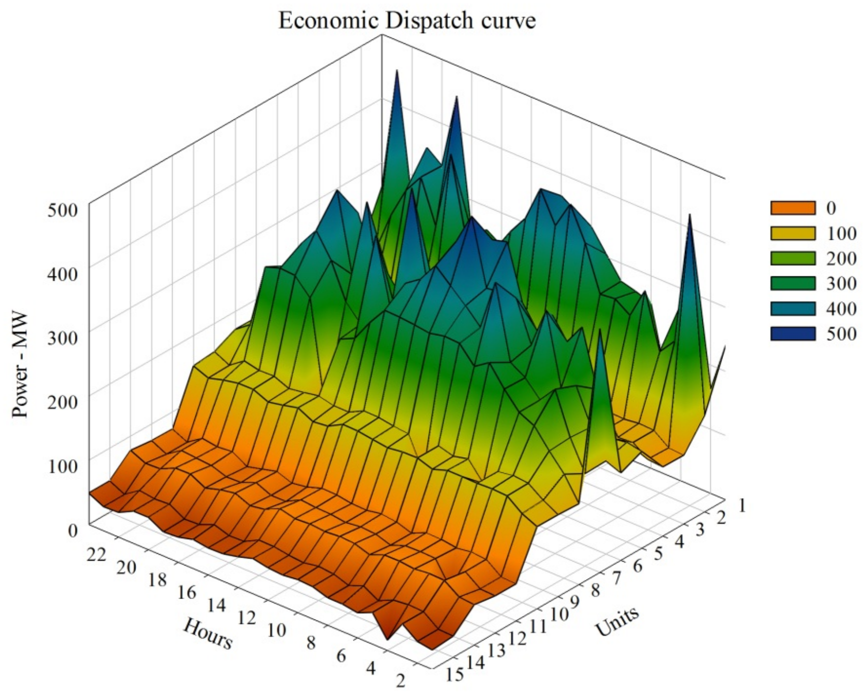

Figure 3.a. Mesh curve of the accomplished ELD in 24 hours.

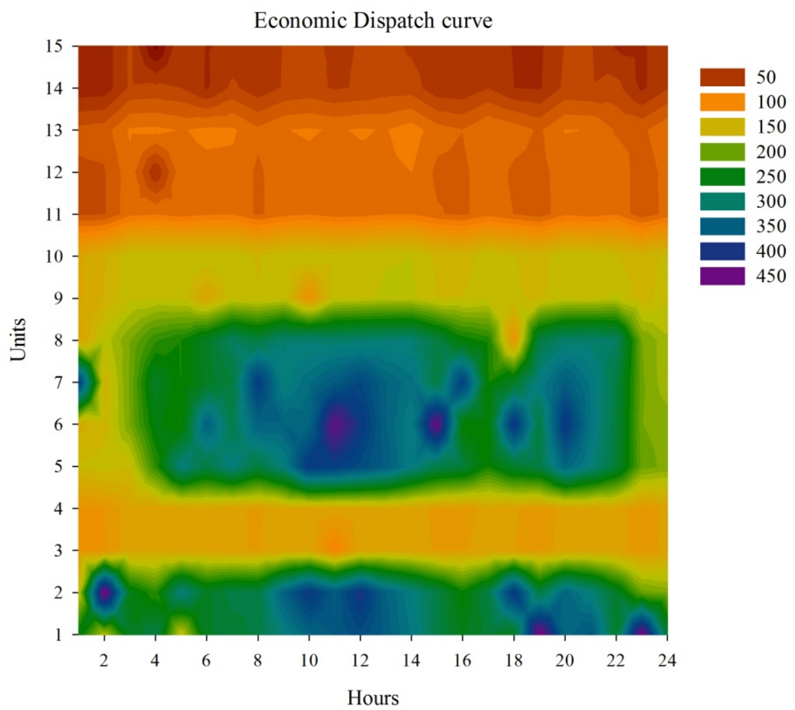

Figure 3.b. Contour curve of the accomplished ELD in 24 hours.

Figure 3. Curve of the accomplished ELD in 15 units' system's test by using PSO algorithm.

6. CONCLUSION

In this article, Economic Load Dispatch among power plants was solved by considering the valve-point loading effects and practical constraints of the power system using particle swarm optimization algorithm (PSO). The proposed method based on PSO algorithm is extremely efficient at presentation of optimal solutions in proper time. In this paper, in addition to the valve-point loading effects, other constraints and power plants' limitations such as: the balance of production and consumption in the system, forbidden zones, the range of production, increasing and decreasing rates, and reliability constraints and modeling network security have been considered. The proposed method of ELD was implemented on a 15-units system and the results have been shown graphically. The results indicate that the proposed algorithm for ELD among power plants has more efficiency than other available algorithms in study resources.

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BIOGRAPHIES OF AUTHORS

Hossein Shahinzadeh: He received his B.S. and M.Sc degrees in Electrical Engineering from Islamic Azad University of Isfahan, Isfahan, Iran and Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran. He is a member of international organizations of IEEE, IET and Institute of Advanced Engineering and Science (IAES) and also an active member of Isfahan's Young Elites Foundation and Isfahan Construction Engineering Organization. His research activities focus on the Smart Grid, Renewable Energies, Energy Management, Distributed Generation & Power System Analysis. He has been a consultant with utilities of Esfahan Electricity Power Distribution Company.

Sayed Mohsen Nasr-Azadani: He recived his B.S. degree in electrical engineering in 2008 from Islamic Azad University Khomeini Shahr Branch, Isfahan, Iran. Now, heis working on the Master's degree in Electrical Engineering from Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran. He received ETO Certificate (Electro Technical Officer) in 2014 From Islamic Republic of Iran Shipping Lines (IRISL Group). He is working on merchant vessels as electrical engineer. His research interest includes Renewable Energy, Energy Management, Power System Analysis and Distributed Generation.

Nazereh Jannesari: She Received her B.S. Degree in Bio Medical Engineering in 2012 from Islamic Azad University Khomeini Shahr Branch, Isfahan, Iran. Now, Sheis working on the Master's degree in Electrical Engineering from Sepahan Institue of Higher Education, Isfahan, Iran. Her research interest includes Signal Processing, Intelligent Optimization Algorithms, Neural Networks, Advanced Microprocessors and Smart Grid.