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Optimal production planning of wind and thermal power plants with respect to constraints on transmission line and taking into account the uncertainty of wind

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Abstract

Diversity and multiplicity of factors affecting the exploitation from power systems, makes completely impossible to solve this problem. Therefore, the optimal planning problem in system exploitation is decomposed into several sub-problems. One of exploitation sub-problems from power systems is economic dispatch of production on system units in order to meet the consumption needs. This is an optimization problem in real power systems, with great dimensions and multiple constraints including economic dispatch of system, transfer network restrictions, rate of increase and decrease in production, prohibited areas of operation units, spinning reserve storage of systems, loading effects of steam valves, multi-fuel production units. A suitable algorithm based on probabilistic search methods has been proposed in order to solve the proposed model effectively in the future. An experimental system with complex solution space is used in order to demonstrate the effectiveness of proposed method and new model and it is compared with some of the latest techniques for solving problem. In this paper, MATLAB software is used for above reviews.

Keywords

Firefly algorithm, optimal production, transmission line constraints, production management, thermal power plant.

1. Introduction

Studies on exploitation of power system lead to find the optimal responses in non-linear spaces with complex calculations. On the other hand artificial intelligence methods unlike purely mathematical methods have the ability to adapt with nonlinear problems and discontinuities which are commonly found in physical systems. Therefore, in recent years using intelligent computational methods, in addition to classic conventional methods of power systems exploitation have become common. So far, many research articles have been presented on using probabilistic search techniques for optimization and control applications. In this plan, a more accurate model of power system economic dispatch is provided. Proposed scheme models the restrictions of increased and decreased production rate, prohibited areas of operation units, spinning reserve systems, loading effects of steam valves, multi-fuel production units and limitations of transmission network that exist concurrently in real power systems. In none of the following references, all these restrictions are considered together. A suitable algorithm based on probabilistic search methods has been proposed in order to solve effectively the proposed model. An experimental system with complex solution space is used in order to demonstrate the effectiveness of proposed method and new model and it is compared with some of the latest techniques for solving problem. In this paper, MATLAB software is used for above reviews.

2. Economic Load dispatch

Economic Dispatch (ED) is the most important task of optimization that plays important role in dispatch and power system performance and control [1], [2]. Implementing ED, the system operator plans the forecasted load demand and power losses in committed production units for economic performance of system in practical constraints. Moreover, for modeling and applying ED problem in

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actual operational power systems, it is necessary to consider spinning reserve requirements (SRRs) in order to overcome errors of production output and unwanted load errors. In practice, the changes in production units output from time to time are limited due to limits in upper and lower slope rate, moreover, opening the great steam turbine steam valve in order to increase the output of units' power results in non-convex characteristic of fuel cost function. Therefore, a practical ED problem must include the effects of valve- point, limits of slope rate and SRR which make it difficult to find the optimal dispatch results. Currently, methods and algorithms of solving ED problem are divided into two categories of methods based on classical optimization and meta- heuristic methods [2]. Methods based on classical optimization methods include linear programming [3], nonlinear programming [4], integer mixed quadratic programming [5], Lagrangian relaxation [6], Lagrangian based on a series of McLaren [7], and dynamic programming [8] have been proposed in order to solve ED regardless of valve- point effects in [3] - [6] and [8] and considering valve- point effects in [7]. Nonlinearity and unevenness of ED problem are ignored so that objective function becomes linear and can lead to large errors in generators' final dispatch of LP method. It is necessary that the objective function becomes differentiable for effective use of NLP and MIQP. Therefore, when NLP and MIQP are implemented to solve the ED problem, some approximations of problem formulation are needed, which may result in large errors of final results. Successful implementation of LR to operator depends on updating Lagrange multipliers and the implementation suffers from response oscillation. DP does not create restrictions on non-convex and roughness of ED problem with valve-point effects [2]. The main defect of DP method is tragedy of dimension when facing ED, especially in large power systems [2]. Thus, methods based on classical mathematical optimization, can provide guarantees of convergence, but don't have classic parameters to be determined. These methods cannot ensure to achieve complete or nearly complete optimal solution; also, they cannot work with CPU execution time, especially under common rugged and non-convex features of valve-point effects [2],[28]. Recently, much interest has been paid to meta-heuristic optimization algorithms for similar reasons; they don't apply any restrictions on problems and consider real-time features and can cope with problems of classical mathematical optimization techniques. Some of the known methods include: Simulated annealing [9], differential evolution [10] to [14], particle swarm optimization [15] to [19], artificial immune system [20], an algorithm based on improved search pattern [21], hybrid evolutionary programming and sequential quadratic programming (EP - SQP) [22], PSO-SQP [23], EP-SQP amended hybrid (MHEP-SQP) [24]. Also, some studies such as [23] and [25] have been proposed in order to solve the ED problem limited to restriction. Two formulations of 60 min SRR are presented in [23] for ED problem. In [25], 10 min SRR is considered for ED in privatized market. A prominent feature of this article is to study ED problem in conjunction with three types of SRR constraints and slope rate limitations. Hence, chaotic search technique has been implemented based on Firefly (FA) algorithm in order to solve RCED problem at real-time and application in power system with real size where the fuel cost of thermal units is minimized. Recently, FA is implemented effectively in order solve economic dispatch through considering generator constraints and uneven cost constraints [26]. Original FA is an evolutionary algorithm based on population that is inspired by effects of firefly lights and charms in summer sky in some areas in order to protect themselves from predators and attract baits [26]. In this optimization problem, the fireflies move to lighter points in order to find complete or near-complete optimal response. Original FA is dependent on its parameters such as absorption coefficients, random motion factor and attraction parameter that is generated by self- adaption [27],[29]. Also, this paper proposes a mutation operator to be added to original FA so that algorithm performance is significantly improved. In fact, the added phase can improve the convergence features and ultimately increase the quality of solutions. Modified FA is new adaptation in order to solve complex and uneven RCED problem using three test systems of implementation. Simulation results show that new modified algorithm finds better solutions while SAMFA convergence is improved effectively compared to FA[30].

3. The formulation of the problem

In this section, we examine the ED formula and its limitations, then we simulate sample systems of 10, 15 and 40 units using proposed algorithm, and discuss on results [29],[30].

3.1. ED formulas and ED with AC restrictions

ED classic model can be summarized as follows.

Min $F_T(P) = \sum_{i=1}^{n} F_i(P_i)$ ***(1)***

This is generally considered as quadratic function

$$F_i(P_i) = a_i + b_i P_i + c_i P_i^2 \qquad \textbf{(2)}$$

The objective function (1,5) is a subject in order to balance voltage and production capacity constraints.

Subject to $\sum_{i=1}^{n} P_i = D + P_{Loss}$ (3)

$$P_i^{\min} \le P_i \le P_i^{\max} \quad i \in n \qquad (4)$$

In problem ED and P are neglected or approximated by unit output function.

$$P_{Loss} = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{n} B_{0i} P_i + B_{00} \qquad (5)$$

3.2. The proposed objective function for ED problem

In practice, the objective function of ED problem has a common point due to effects of multi-fuel and steam valves effects. A sinusoidal function is added to modify cost function in order to consider steam valves effects.

$$F_i(P_i) = a_i + b_i P_i + c_i P_i^2 + \left| e_i \sin(f_i (P_i^{\min} - P_i)) \right| \qquad (6)$$

Where a, b, c, e, f are fuel cost coefficient of i[th] unit with loading effects of steam valves. In addition, there are many production units that are fed with multi- fuel. In this case, we show cost function with multi- partial function contrary to custom.

$$F_i(P_i)\begin{cases} a_{i1} + b_{i1}P_i + c_{i1}P_i^2 & fuel1, P_i^{\min} \le P_i \le P_{i1}^{\max} \\ a_{i2} + b_{i2}P_i + c_{i2}P_i^2 & fuel2, P_{i2}^{\min} \le P_i \le P_{i2}^{\max} \\ \vdots & \vdots \\ a_{ij} + b_{ij}P_i + c_{ij}P_i^2 & fuelj, P_{ij}^{\min} \le P_i \le P_i^{\max} \end{cases} \qquad (7)$$

Remarkably , $P_{ij-1}^{\max} = P_{ij}^{\min}$

Therefore, we consider cost function as below in order to involve effects of steam valve and multi fuel.

$$F_i(P_i) = a_{ij} + b_{ij}P_i + c_{ij}P_i^2 + \left| e_{ij} \sin(f_{ij}(P_{ij}^{\min} - P_i)) \right|$$
$$if fuel j, P_{ij}^{\min} \le P_i \le P_{ij}^{\max}$$
$$j = 1, \ldots, N_{fi} and i = 1, \ldots, n. \qquad (8)$$

where Pij is i[th] unit output with j[th] fuel. We use ED and ED with AC constraints in order to model the cost function with a hybrid objective function.

3.3. Limitations

3.3.1. Limitations of slope rate per power plant (steam- gas- nuclear and so on)

Slope rate has specific increased or decreased power rate where this rate is 11 MB per minute in gas power plants. We show this constraint as below.

$$\begin{cases} P_i - P_{0i} \le UR_i, & if generation increases \\ P_{0i} - P_i \le DR_i, & if generation decreases \end{cases} \qquad (9)$$

Therefore, the production capacity constraints are modified as follows:

$$\max(P_i^{\min}, P_{oi} - DR_i) \le P_i \le \min(P_i^{\max}, P_{oi} + UR_i)$$
$$i = 1, \ldots, n \qquad (10)$$

Here, the increased rate slope is based on output power of units in previous hours

3.3.2. Restricted areas of operation

There are points in production range of units where exploitation is prohibited because these points can damage this equipment during exploitation. For i unit with Poz , access to exploitation areas is described as follows.

$$\begin{cases} P_i^{\min} \le P_i \le P_{i,1}^{LB} & \\ P_{i,j-1}^{UB} \le P_i \le P_{i,j}^{LB} & j = 2,3,\ldots, NP_i \\ P_{i,j}^{UB} \le P_i \le P_i^{\max} & j = NP_i \end{cases} \qquad (11)$$
$$For i = 1,2,\ldots, N_{GP}$$

3.3.3. Battalion reserve of system due to limitations of Poz

This limitation is as follows.

$$S_i = \begin{cases} \min\{(P_i^{\max} - P_i), S_i^{\max}\} & \forall i \in (\Omega - \Theta) \\ 0 & \forall i \in \Theta \end{cases}$$

(12)

$$S_r = \sum_{i=1}^{n} S_i$$

(13)

$$S_r \ge S_R$$

(14)

Restriction dispatch of unit production can be calculated from proposed formulas. Although these restrictions are usually considered in UC (OPF), the proposed model for non- even restrictions of AD problem includes objective function based on formulas (1) and (8) and constraints of (3), (10), (11), (12) and (14).

3.3.4. limitations of power balance (AC Power Flow)

$$P_{Gi} - P_{Di} = V_i \sum_{j=1}^{N} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \quad i \in N_{B-1} \tag{15}$$

$$Q_{Gi} - Q_{Di} = V_i \sum_{j=1}^{N} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \quad i \in N_{PQ} \tag{16}$$

3.3.5. limitations of Security

These restrictions are related to sustainability.

$$V_i^{\min} \le V_i \le V_i^{\max} \quad i \in N_{B-1} \tag{17}$$

$$\left| BF_i \le BF_i^{\max} \right| \quad i \in N_b \tag{18}$$

$$V_{ir}^{\min} \le V_{ir} \le V_{ir}^{\max} \quad i \in N_{B-1}, r \in S_C \tag{19}$$

$$\left| BF_{ir} \le BF_{ir}^{\max} \right| \quad i \in N_b, r \in S_C \tag{20}$$

Here Sc is a set of acceptable possibilities that may be obtained from probability ranking method.

3.3.6. limitations of reactive power production

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad i \in n \tag{21}$$

3.3.7. Real losses

Actual losses of network in ED with AC restrictions are modeled as follows.

$$P_{Loss} = \sum_{k=1}^{N_b} G_k [V_i^2 + V_j^2 - 2V_i V_j \cos(\theta_{ij})] \tag{22}$$

The proposed model for ED with AC restrictions is modeled like ED objective function with constraints of (10), (11), (12) and (14).

4. Using FA algorithm for solving the economic dispatch problem and optimal production

For this purpose, FA is used as an evolution-based optimization algorithm. Original FA has defect similar to PSO and GA, it is depended on initial regulating parameters. Two adaptive phase-change and adjustment is suggested in order to overcome defect of FA that will increase appropriately the ability to general search of algorithm. The proposed change method will reduce the dependence of FA to initial parameters while it will increase the algorithm convergence speed. Various equal and unequal numbers of constraints must be met in order to solve the problem of optimal production during the optimization process. Feasibility and superiority of proposed method has been tested [28],[29].

4.1. Adaptive Modified FA (AMFA)

In this section, a recent modification is suggested effectively in order to improve the search ability of Firefly. The proposed modification method consists of two phases in order to increase the accuracy and convergence speed of FA. The first part of method is used to update α value as adaptive randomization parameter in range of (0, 1). Large amount of α encourages Firefly to search in unknown areas while a small amount forces Firefly to search locally. Therefore, an adaptive formulation is proposed that manages α value during optimization as follows.

$$\alpha^{k+1} = \left(\frac{1}{2k_{\max}} \right)^{1/k_{\max}} \alpha^k \tag{24}$$

Where k is iteration number and k_{max} is the maximum number of iterations. The second part of modification method is to increase the population of fireflies through mutation and crossover operators. To this end, three random Fireflies (n1, n2, n3) are chosen for each Firefly (Xi), so that (n1 ≠ n2 ≠ n3 ≠ i). A test solution is produced as follows:

$$X_{Test} = X_{n1} + \sigma_1 \times (X_{n2} - X_{n3})$$
$$X_{Test} = [x_{Test,1}, x_{Test,2}, \ldots, x_{Test,d}] \tag{25}$$

where σ is random value in the range of [0, 1]. Now, using Xi, X_{Test} and the best Firefly (X_{best}), two fireflies are produced as follows:

$$x_{new1,j} = \begin{cases} x_{Test,j}, & if \sigma_1 \le \sigma_2 \\ x_{best,j}, & otherwise \end{cases}$$

(26)

$$X_{new,2} = \sigma_3 \times X_{best} + \sigma_4 \times (X_{best} - X_j) \quad (27)$$

where $\sigma_1 \dots, \sigma_4$ are random values in the range of [0, 1], respectively. The best Firefly is selected among X_{new1} and X_{new2} and is compared with i^{th} Firefly (X_i). If this Firefly was better than Xi, it will replace Xi, otherwise, Xi remains in its position.

4.2. Steps of proposed algorithm

In summary, the steps of algorithms for solving the problem are as follows:

Step 1: Define the input data. At this step, all data including network data, algorithm data, parameters of objective function and constraint parameters are fully defined.
Step 2: Production of initial population (Fireflies).
Step 3: Production of objective functions separately for each firefly. At this step, the objective function value is produced.
Step 4: Production of attractiveness using equation (4-5) for each firefly.
Step 5: Apply the equation (4-6) between two fireflies in order to measure the distance.
Step 6: Move the Firefly with less brightness towards attractive Firefly (brighter) by equation (4-7).
Step 7: Apply the modified phase according to previous section.
Step 8: Update process. The initial population is updated using modified new fireflies.
Step 9: Study the stopping criterion. If the stopping criterion is met, stop algorithm and publish results, otherwise go back to step 4 and repeat the process.

5. Simulation Results

5.1. The first test system- a system of 10 units

The test system consists of ten power units with valve-point effects and multiple selection of fuel for load demand of 2700 MW. System information is shown in Table 1.[28]

Table 1: The first test system information with 10 power units [28]

unit	Generation Min P1 P2 max F1 F2 F3	Fuel type	Coefficient				
			A1	**B1**	**C1**	**E1**	**F1**
1	100 196 250 1 2	1 2	.2697e2 .2113e2	-.3975e0 -.3059e0	.2176e-2 .1861e-2	.2697e-1 .2113e-1	-.3975e1 -.3059e1
2	50 114 157 230 2 3 1	1 2 3	.1184e3 .1865e1 .1365e2	-.1269e1 -.3988e-1 -.1980e0	.4194e-2 .1138e-2 .1620e-2	.1184e0 .1865e-2 .1365e-1	-.1269e2 -.3988e0 -.1980e1
3	200 332 388 500 1 3 2	1 2 3	.3979e2 -.5914e2 -.2875e1	-.3116e0 .4864e0 .3389e-1	.1457e-2 .1176e-4 .8035e-3	.3979e-1 -.5914e-1 -.2876e-2	-.3116e1 .4864e1 .3389e0
4	99 138 200 256 1 2 3	1 2 3	.1983e1 .5285e2 .2668e3	-.3114e-1 -.6348e0 -.2338e1	.1049e-2 .2758e-2 .5935e-2	.1983e-2 .5285e-1 .2668e-0	-.3114e0 -.6348e1 -.2338e2
5	190 338 407 490 1 2 3	1 2 3	.1392e2 .9976e2 -.5399e2	-.8733e-1 -.5206e0 .4462e0	.1066e-2 .1597e-2 .1498e-3	.1392e-1 .9976e-1 -.5399e-1	-.8733e0 -.5206e1 .4462e1
6	85 138 200 256 2 1 3	1 2 3	.5285e2 .1983e1 .2668e3	-.6348e0 -.3114e-1 -.2338e1	.2758e-2 .1049e-2 .5935e-2	.5285e-1 .1983e-2 .2668e0	-.6348e1 -.3114e0 -.2338e2
7	200 331 391 500 1 2 3	1 2 3	.1893e2 .4377e2 -.4335e2	-.1325e0 -.2267e0 .3559e0	.1107e-2 .1165e-2 .2454e-3	.1893e1 .4377e-1 -.4335e-1	-.1325e1 -.2267e1 .3559e1

8	99 138 200 256 1 2 3	1 2 3	.1983e1 .5285e2 .2668e3	-.3114e-1 -.6348e0 -.2338e1	.1049e-2 .2758e-2 .5935e-2	.1983e-2 .5285e-1 .2668e0	-.3114e0 -.6348e1 -.2338e2
9	130 213 370 440 3 1 3	1 2 3	.8853e2 .1530e2 .1423e2	-.5675e0 -.4514e-1 -.1817e-1	.1554e-2 .7033e-2 .6121e-3	.8853e-1 .1423e-1 .1423e-1	-.5675e1 -.1817e0 -.1817e0
10	200 362 407 490 1 3 2	1 2 3	.1397e2 -.6113e2 .4671e2	-.9938e-1 .5084e0 - .2024e0	.1102e-2 .4164e-4 .1137e-2	.1397e-1 -.6113e-1 .4671e-1	-.9938e0 .5084e1 -.2024e1

The simulation results of first test network are shown in Table 2 and are compared with other methods. As you can see, the cost of proposed FA algorithm is less than other methods.

Table 2: Simulation results on first test network

Method	Best	Average	Worst
CGA_MU [125]	624.7193	627.6093	633.8652
IGA_MU [125]	624.5178	625.8692	630.8705
DE [126]	624.5146	624.5246	624.5458
RGA [126]	624.5081	624.5079	624.5088
PSO [126]	624.5074	624.5074	624.5074
PSO-LRS [127]	624.2297	624.7887	628.3214
NPSO[127]	624.1624	625.218	627.4237
NPSO-LRS [127]	624.1273	625.9985	626.9981
The proposed Method	623.8839	623. 9346	623.9873

The convergence speed curve of FA algorithm is displayed in Figure up to 600 repeats

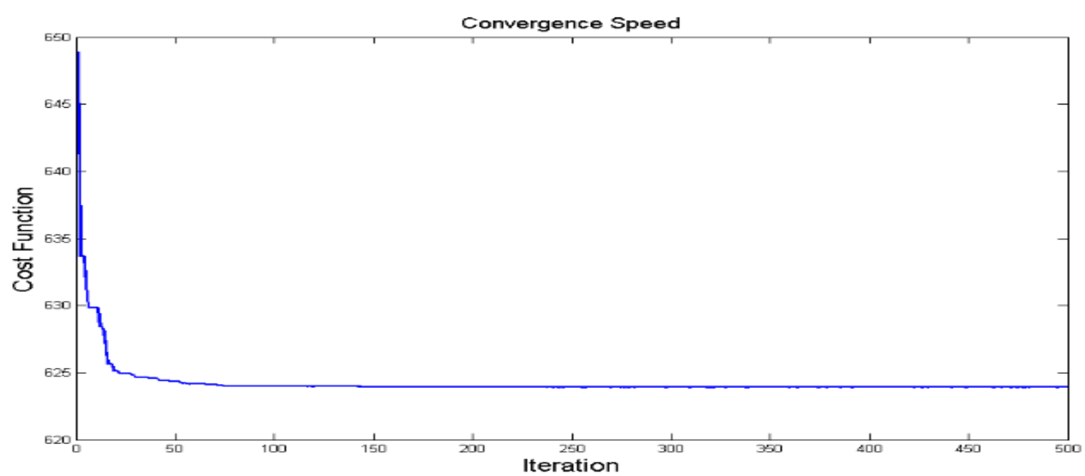

Figure 1: Algorithm convergence speed curve in the 10 units system

5.2. The second test system- a system of 15 units

The system includes 15 thermal units and their characteristics are given in Tables 3 and 4. System load demand is 2630 MW and loss coefficients matrix is shown below.[31].

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Table 3: Second test system information- test system with 15 production units [31]

unit	$P_i^{\min}$	$P_i^{\max}$	α_1 (S)	β_1 (S/MW)	γ_1 (S/MW2)	URi (MW/h)	DRi (MW/h)	P_i^0
1	150	455	671	10.1	0.000229	80	120	400
2	150	455	574	10.2	0.000183	80	120	300
3	20	130	374	8.8	0.001126	130	130	105
4	20	130	374	8.8	0.001126	130	130	100
5	150	470	461	10.4	0.000205	80	120	90
6	135	460	630	10.1	0.000301	80	120	400
7	135	465	548	9.8	0.000364	80	120	350
8	60	300	227	11.2	0.000338	65	100	95
9	25	162	173	11.2	0.000807	60	100	105
10	25	160	175	10.7	0.001203	60	100	110
11	20	80	186	10.2	0.003586	80	80	60
12	20	80	230	9.9	0.005513	80	80	40
13	25	85	225	13.1	0.000371	80	80	30
14	15	55	309	12.1	0.001929	55	55	20
15	15	55	323	12.4	0.004447	55	55	20

Table 4: Restricted areas of second test system production [31]

Unit	Prohibited Zones (MW)
2	[185 225] [305 335] [420 450]
5	[180 200] [305 335] [390 420]
6	[230 255] [365 395] [430 455]
12	[30 40] [55 65]

Losses coefficients Matrix of second test system is as follows:[31]

$$
\begin{matrix}
0.0014 & 0.0012 & 0.0007 & -.0001 & -0.0003 & -0.0001 & -0.0001 & -0.0001 & -0.0003 & 0.0005 & -0.0003 & -0.0002 & 0.0004 & 0.0003 & -0.0001 \\
0.0012 & 0.0015 & 0.0013 & 0.0000 & -0.0005 & -0.0002 & 0.0000 & 0.0001 & -0.0002 & -0.0004 & -0.0004 & -0.0000 & 0.0004 & 0.0010 & -0.0002 \\
0.0007 & 0.0013 & 0.0076 & -0.0001 & -0.0013 & -0.0009 & -0.0001 & 0.0000 & -0.0008 & -0.0012 & -0.0017 & -0.0000 & -0.0026 & 0.0111 & -0.0028 \\
-0.0001 & 0.0000 & -0.0001 & 0.0034 & -0.0007 & -0.0004 & 0.0011 & 0.0050 & 0.0029 & 0.0032 & -0.0011 & -0.0000 & 0.0001 & 0.0001 & -0.0026 \\
-0.0003 & -0.0005 & -0.0013 & -0.0007 & 0.0090 & 0.0014 & -0.0003 & -0.0012 & -0.0010 & -0.0013 & 0.0007 & -0.0002 & -0.0002 & -0.0024 & -0.0003 \\
-0.0001 & -0.0002 & -0.0009 & -0.0004 & 0.0014 & 0.0016 & -0.0000 & -0.0006 & -0.0005 & -0.0008 & 0.0011 & -0.0001 & -0.0002 & -0.0017 & 0.0003 \\
-0.0001 & 0.0000 & -0.0001 & 0.0011 & -0.0003 & -0.0000 & 0.0015 & 0.0017 & 0.0015 & 0.0009 & -0.0005 & 0.0007 & -0.0000 & -0.0002 & -0.0008 \\
-0.0001 & 0.0001 & 0.0000 & 0.0050 & -0.0012 & -0.0006 & 0.0017 & 0.0168 & 0.0082 & 0.0079 & -0.0023 & -0.0036 & 0.0001 & 0.0005 & -0.0078 \\
-0.0003 & -0.0002 & -0.0008 & 0.0029 & -0.0010 & -0.0005 & 0.0015 & 0.0032 & 0.0129 & 0.0116 & -0.0021 & -0.0025 & 0.0007 & -0.0012 & -0.0072 \\
-0.0005 & -0.0004 & -0.0012 & 0.0032 & -0.0013 & -0.0008 & 0.0009 & 0.0079 & 0.0116 & 0.0200 & -0.0027 & -0.0034 & 0.0009 & -0.0011 & -0.0088 \\
-0.0003 & -0.0004 & -0.0017 & -0.0011 & 0.0007 & 0.0011 & -0.0005 & -0.0023 & -0.0021 & -0.0027 & 0.0140 & 0.0001 & 0.0004 & -0.0038 & 0.0168 \\
-0.0002 & -0.0000 & -0.0000 & -0.0000 & -0.0002 \cdots & -0.0001 & 0.0007 & -0.0036 & -0.0025 & -0.0034 & 0.0001 & 0.0054 & -0.0001 & -0.0004 & 0.0028 \\
0.0004 & 0.0004 & -0.0026 & 0.0001 & -0.0002 & -0.0002 & -0.0000 & 0.0001 & 0.0007 & 0.0009 & 0.0004 & -0.0001 & 0.0103 & -0.0101 & 0.0028 \\
0.0003 & 0.0010 & 0.0111 & 0.0001 & -0.0024 \ddots & -0.0017 & -0.0002 & 0.0005 & -0.0012 & -0.0011 & -0.0038 & -0.0004 & -0.0101 & 0.0378 & -0.0094 \\
-0.0001 & -0.0002 & -0.0028 & -0.0026 & -0.0003 \cdots & 0.0003 & -0.0008 & -0.0078 & -0.0072 & -0.0088 & 0.0168 & 0.0028 & -0.0028 & -0.0094 & 0.1283
\end{matrix}
$$

Boi=[-0.0001 -0.0002 0.0028 -0.0001 0.0001 -0.0003 -0.0002 -0.0002 0.0006 0.0039 -0.0017 -0.0000 -0.0032 0.0067 -0.0064]

Boo=0.0055

Firstly, simulation was done using proposed FA algorithm on second test network. Table 5 shows the simulation results and compares the results of proposed FA algorithm with GA and PSO algorithms. As can be seen, the cost of proposed FA algorithm is declined compared to other algorithms, but in the case of PSO algorithm, the cost in the best case has very small difference with FA algorithm, but in general, the cost is declined with FA algorithm[28],[31].

Table 5: Simulation results on second test network

Method	Best	Average	Worst
GA	33,113.0	33,228.0	33,337.0
PSO	32,858.0	33,039.0	33.331.0
The proposed Method	32,680.5956	32,687.3305	32,693.2641

Figure 2 shows the converge curves for 15 units system.

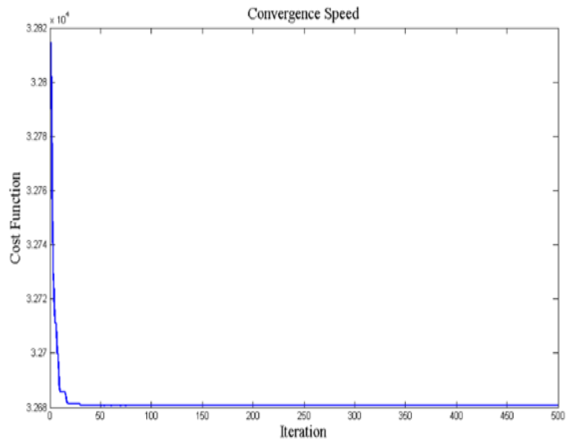

Figure 2: Converge curve for 15 units system

5.3. The third test system- a system of 40 units

The test system consists of 40 production units, with changes in order to reload the valve- points.

Table 6 compares the simulation results of proposed FA algorithm and other optimization algorithms and it can be seen that cost is reduced using proposed FA algorithm.

Table 6: Simulation results on third test network

Method	Best	Average	Worst
IFEP [102]	122,624.3500	123,382.0000	125,740.6300
MPSO [128]	122,252.2650	NA	NA
ESO [103]	122,122.1600	122,558.4565	123,143.0700
PSO-LRS [127]	122,035.7946	122,558.4565	123,461.794
Improved GA [129]	121,915.9300	122,811.4100	123,334.0000
HPSOWM [130]	121,915.3000	122,844.4	NA
IGAMU[131]	121,819.2521	NA	NA
NPSO [127]	121,704.7391	122,221.3697	122,995.0976
HDE[132]	121,698.5100	122,304.3000	NA
NPSO-LRS [127]	121,664.4308	122,209.3185	122,981.5913
The proposed Method	121,578.4832	121,583.3029	121,601.0001

Figure 3 shows the converge curve for 40 units system.

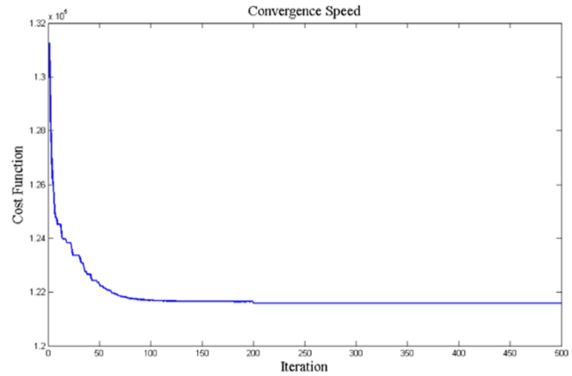

Figure 3: The converge curve for 40 units system

6. Conclusion

The main objective of this paper is to solve practical non- convex economic dispatch. For this purpose, a practical formulation was proposed for Economic Dispatch in order to model appropriately the limitations of system. Then, a new firefly modified algorithm was proposed in order to increase general ability of algorithm search for local and comprehensive search. The proposed method was tested on three test systems. Using optimization ability, the advantages of proposed MFA on other algorithms. Also, it can be seen that considering the uncertain amount in this problem will change the optimal value of cost objective function so that considering it will lead to impractical results. The feasibility and satisfactory performance of proposed method was seen in all three tests cases. For research advancement the following cases are proposed: working on power systems with multi-objective ED and RCDED problems, considering emissions of CO2, involving new energies such as Wind Turbine, solar energy (with uncertainty of sunshine), tidal energy (with an uncertainty of water waves), geothermal energy and micro- turbines presence. The simulation of uncertainty with regard to load forecast errors and accidents in production units can help to improve the work.

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