# Flower Pollination Algorithm for Solving Economic Dispatch Problems with Prohibited Operating Zones and Multiple Fuel Options

**Y. V. Krishna Reddy, M. Damodar Reddy**

***Abstract:** A nature inspired optimization algorithm based on the transfer of pollen in universe called the Flower Pollination Algorithm, is implemented for solving economic dispatch (ED) problems with considering prohibited operating zones (POZs), and multiple fuel options including valve-point loading. The proposed method mainly depends on biotic pollination for transfer of pollens by using pollinators such as birds and insects, in order to find the survival of the fittest and the optimal reproduction of flowering plants. This algorithm has been exercised on three test systems (6, 15 and 10 units) with POZS and multiple fuel options for solving ED problems. The numerical results are compared with results of some new methods to verify the quality of FPA for solving ED problems. The result analyses prove the effectiveness of the FPA algorithm and show that it could be outlasts technique for solving ED problems in terms of total cost and computational time.*

***Index Terms:** Economic Dispatch, Flower Pollination Algorithm, Prohibited Operating Zones, Multiple Fuels, Valve-Point Loading.*

## I. INTRODUCTION

The system deals with power generation, transmission and distribution in order to supply the electrical energy to the consumers on economical basis known as power systems. In power systems Economic Dispatch (ED) is the major problem, to allocating the required load between the generation units such that the operation cost is minimized and operational imperatives. In the ED problem, the each generation unit cost function characterized by a single quadratic function and the problem is solved using lambda iteration method [1], quadratic programming [2] and linear programming [3] methods. These classical methods are required mathematical limitations such as derivatives, convexity and linear objectives to solve the ED problem.

An ED problem is non-convex due to the behaviour of generation units' input-output characteristics, which cannot be solved directly by using mathematical approaches. Eventhough dynamic programming (DP) [4] can solve type of problems, but it suffers from curse of dimensionality. Advanced methods such as particle swarm optimization (PSO) [5], differential evolution (DE) [6], genetic algorithm (GA) [7] and biogeography based optimization (BBO) [8] are developed to solve these problems. PSO showed promising option to solve practical ED problems, since they can handle ramp up/down limits and prohibited operating zones (POZs) constraints. Other methods in this category, including multiple tabu search (MTS) algorithm [9], clonal algorithm (artificial immune system) [10], mixed integer programming [11], hybrid differential evolution (HDE) [12], exchange market algorithm (EMA) [13], and backtracking search algorithms (BSA) [14] are developed to solve these problems.

In practical power system, many thermal generating units are supplied with multiple fuels like oil, natural gas and coal. In this case, the ED problem generation cost function is no longer represented as a single quadratic function but non-smooth piecewise quadratic function and it can be solved by crisscross optimization (CSO) [15] algorithm. Few older methods such as hierarchical economic dispatch [16], Hopfield neural network (HNN) [17-18], PSO [19], improved GA [20], and hybrid selfadaptive DE with augmented lagrange multiplier (SADE_ALM) [21] methods are used to solve piecewise quadratic cost function ED problem. Further recently some methods are developed such as oppositional invasive weed optimization (OIWO) [22], modified PSO [23], grey wolf optimization (GWO) [24], and modified symbiotic organism search (SOS) [25] are used to multiple fuel ED problem.

In order to solve ED problem valve point loading, ramp rate limits, POZs, and multiple fuels are require to consider, it's extremely hard to finding optimal solution. In this paper, Flower Pollination Algorithm (FPA) has been proposed and implemented to solve ED problem with above mentioned constraints. The quality of the proposed method has been applied to three different test systems for solving ED problem.

## II. PROBLEM FORMULATION

In order to minimize the cost of operation, Economic Dispatch (ED) is the process of optimal allocation of available generation units to meet the required load demand. In general, the generation cost function represented as a second order function, as shown in Eqn. (1).

$$F_k(P_{Gk}) = a_k P_{Gk}^2 + b_k P_{Gk} + c_k \tag{1}$$

Where $a_k$, $b_k$ and $c_k$ are coefficients of generator k.

The objective function is minimizing to generation cost as shown in Eqn. (2).

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**Y. Venkata Krishna Reddy,** Department of Electronics and Electrical Engineering, Sri Venkateswara University, Tirupati (Andhra Pradesh), E-mail: yvkrishnareddy36@gamil.com

**Dr. M. Damodar Reddy,** Department of Electronics and Electrical Engineering, Sri Venkateswara University, Tirupati (Andhra Pradesh), India.

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$$F = \min f = \sum_{k=1}^{n} F_k(P_{Gk}) \qquad (\$/h) \tag{2}$$

Where $F_k$ denotes total generation cost for the generator unit k, which is defined in Eqn. (1).

In practical power system cost function is non-convex, because due to discontinuities of turbine-generator (valve-point loading) added sinusoidal terms to the second order cost functions as follows Eqn. (3).

$$F_2 = F_C(P_G) = \sum_{k=1}^{N_G} (a_k P_{Gk}^2 + b_k P_{Gk} + c_k) + \left| e_{ck} \times \sin(f_{ck} \times (P_{Gk}^{min} - P_{Gk})) \right| \qquad (\$/h) \tag{3}$$

Where $e_{ck}$ and $f_{ck}$ are constants of the unit-k due to discontinuities of generating unit.

In practical power system operation, thermal units supplied with multiple fuels and also valve points for controlling power outputs. The generation cost function can be formulated due to the multiple fuels and valve-point loading as shown in Eqn. (4).

$$F_C(P_{Gk}) = \begin{cases} a_{k1}P_{Gk}^2 + b_{k1}P_{Gk} + c_{k1} + \left| e_{ck1} \times \sin(f_{ck1} \times (P_{Gk}^{min} - P_{Gk})) \right| \\ \qquad P_{Gk}^{min} \le P_{Gk} \le P_{Gk1} \\ a_{k2}P_{Gk}^2 + b_{k2}P_{Gk} + c_{k2} + \left| e_{ck2} \times \sin(f_{ck2} \times (P_{Gk}^{min} - P_{Gk})) \right| \\ \qquad P_{Gk1} \le P_{Gk} \le P_{Gk2} \\ . \\ . \\ . \\ a_{kn}P_{Gk}^2 + b_{kn}P_{Gk} + c_{kn} + \left| e_{ckn} \times \sin(f_{ckn} \times (P_{G}^{min} - P_{Gk})) \right| \\ \qquad P_{Gk(n-1)} \le P_{Gk} \le P_{Gk}^{max} \end{cases} \tag{4}$$

### 2.1. Equality Constraint

Total generation of any power system must meet the required load demand and losses occur in the transmission lines, as shown in Eqn. (5).

$$\sum_{k=1}^{N_G} P_{Gk} = P_D + P_L \tag{5}$$

Where $P_L$ denotes power losses and $P_D$ denotes the power demand. The power loss can be computed using B-coefficient method expressed as a second order function shown in Eqn. (6).

$$P_L = \sum_{j=1}^{n}\sum_{k=1}^{n} P_{Gj} B_{jk} P_{Gk} + \sum_{j=1}^{n} B_{0j} P_{Gj} + B_{00} \qquad (MW) \tag{6}$$

### 2.2. Power Limit Constraint

Any generator output can be varied between minimum and maximum power limits as follows Eqn. (7).

$$P_{Gk}^{min} \le P_{Gk} \le P_{Gk}^{max} \tag{7}$$

### 2.3. Ramp Rate Limits

The online unit's generation level not exceed its ramp rate limitation between two successive periods.

When power increases, we have

$$P_k - P_k^0 \le UR_k \tag{8}$$

When power decreases, we have

$$P_k^0 - P_k \le DR_k \tag{9}$$

Where $P_k^0$ : The previous power generation of unit k.

$UR_k$ : Ramp-up limit of the kth generator.

$DR_k$ : Ramp-down limit of the kth generator.

The inclusion of ramp-up/down limits changes the generator operation limits Eqn. (10) as follows:

$$\max(P_k^{max}, UR_k - P_k) \le P_k \le \min(P_k^{max}, P_k - DR_k) \tag{10}$$

### 2.4. Prohibited Operating Zones

A generator with POZs whole operating region will be divided into several isolated sub-regions. The conception of POZs is consisted of the following constraint in the ED:

$$\begin{cases} P_{Gj}^{min} \le P_{Gj} \le P_{Gj1}^{LB} \\ \text{............} \\ P_{Gj,k-1}^{UB} \le P_{Gj} \le P_{Gj,k}^{LB} \quad k = 2,3,4.......NP_j \\ P_{Gj,k}^{UB} \le P_{Gj} \le P_{Gj}^{max} \quad k = NP_j \end{cases} \tag{11}$$

Where $P_{j,k}^{LB}$ : Lower boundary of POZ k of generator j.

$P_{j,k}^{UB}$ : Upper boundary of POZ k of generator j.

$NP_j$ : The number of POZs of generator j.

## III. FLOWER POLLINATION ALGORITHM

In this paper, new optimization algorithm based on flower pollination process has been proposed and implemented on ED problem. FPA was developed by Xin-She Yang [26] in 2012. There are namely two types of pollination processes known as biotic and abiotic. Majorly (90%) the transfer of pollen occurs due to the biotic pollination by using pollinators as bats, birds, insects and other animals. Wind and diffusion help in the abiotic pollination (10% occur) rather than using pollinators.

Flower pollination can be achieved by either cross-pollination or self-pollination. First one is occur due to pollination from pollen of a flower of different plants. Second one is occur due to pollination of one flower from pollen of the same flower or other flowers of the same plant.

For FPA, the following four rules are used:

1. To find the global fittest, biotic and cross pollination considered, as pollen – carrying pollinators fly following Levy flights.
2. To find the local fittest, abiotic pollination and Self-pollination used.
3. Generally insects can develop flower perseverance; this probability of reproduction is proportional to the similarity of the two flowers involved.
4. The switch probability of $P \, \varepsilon [0,1]$, is used to control interaction of local and global pollination, which is slightly biased toward local pollinator.

3.1 Mathematical representation of FPA

Global fittest ($g_*$) can be formulated using first rule, and it can be represented mathematically as Eqn. (12),

$$X_i^{t+1} = X_i^t + L(X_i^t - g_*) \qquad (12)$$

Where $X_i^t$ the solution is vector $X_i$ at iteration t, and $g_*$ is the current iteration best solution. L is the strength of pollination should be greater than zero.

Levy distribution can be represent as Eqn. (13)

$$L \sim \frac{\lambda\Gamma(\lambda)*\sin(\pi\lambda/2)}{\pi}\left(\frac{1}{S^{1+\lambda}}\right) \qquad (S \gg S_0 > 0) \qquad (13)$$

Where Γ (λ) is Standard gamma function and this distribution is valid for large steps S > 0.

For the local pollination, both Rule 2 and Rule 3 can be represented as shown in Eqn. (14).

$$X_i^{t+1} = X_i^t + \varepsilon(X_j^t - X_k^t) \qquad (14)$$

Here $X_j^t$ and $X_k^t$ are pollens from the different flowers of the same plant species. Here ε is drawn from a uniform distribution as [0, 1]. Flower pollination can occur at both local and global search. If two solutions are similar, the search can be local; while two solutions are different then the search will be global. The population size n and probability switch (p ∈ [0, 1]) are the two parameters in this algorithm. From our simulations, we found that p= 0.8 works better for most applications. The flower pollination flowchart shown if Fig. 1, and algorithm to the proposed method discussed in below.

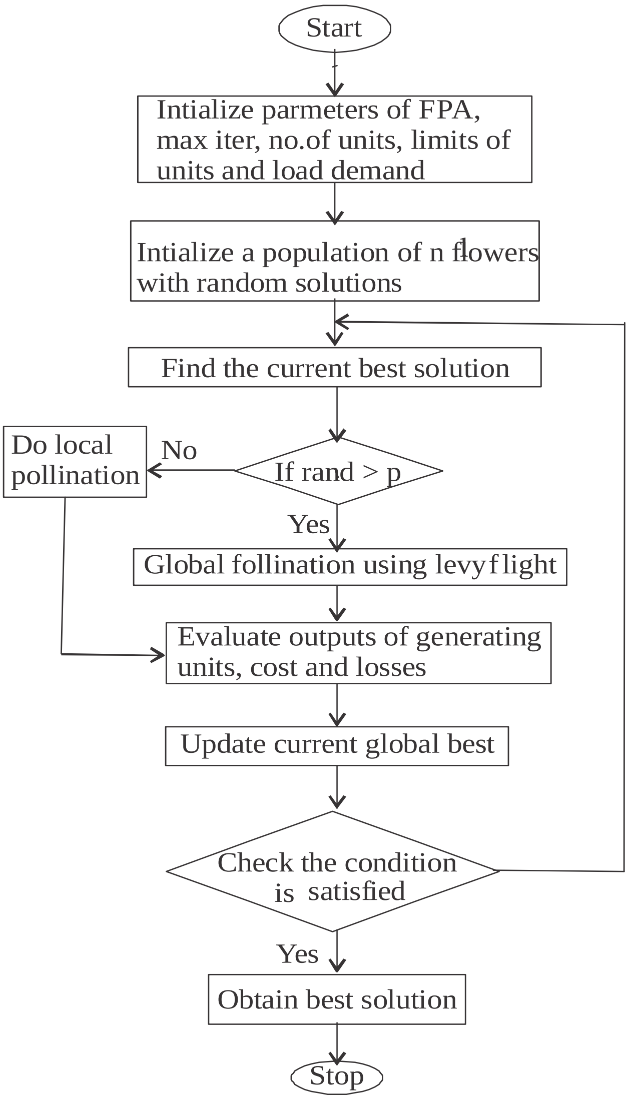

**Fig. 1. Flowchart of FPA to solve ELD**

**Implementation of Flower Pollination Algorithm:**

**Step 1:** The algorithm starts by setting the initial values of the population size(n), switch probability(p), maximum number of iterations, dimension of search variables (dim), coefficients of generation cost, B-matrix, upper & lower limits and load demand.

**Step2:** Initialize the population or solutions of flower randomly.
Sol (i, :) =Lb+ (Ub-Lb).*rand (1, dim).

**Step3:** Find the current best solution $g_*$ in the initial population.
[Fmin, I]=min (Fitness).

**Step4**: Start the iteration count i=1.

**Step5:** Check the simple limits. If random is greater than p, Draw a step vector which obeys a levy distribution using equation (12). Do the global pollination using Eqn. (13).

**Step6:** If random is less than p, Draw a uniform distribution in [0, 1] randomly choose j & k among all the solutions. Do the local pollination using equation (14).

**Step7:** Check if all the constraints are satisfied if not satisfied go to step 4. Evaluate new solutions (outputs of generating units, cost and losses).

**Step8:** Update the global fittest and its position.

**Step9:** Display the results such as generation cost, power generations, transmission losses and total power generation.

## IV. NUMERICAL RESULTS

In this section, to access the potential of the proposed FPA method, three different systems are considered. The description of test systems as follows:

1. 6-unit system with ramp up/down limits, POZs and losses.
2. 15-unit system with ramp up/down limits, POZs and losses.
3. 10-unit system with multiple fuels, valve-point loading (without/with) and losses.

The proposed algorithm has been implemented in MATLAB R2014a and executed on personal computer to solve ED problems. To validate the robustness of the proposed method for each test system, the no.of 30 trails is considered. In all test systems, the number of search agents is 40.

### 4.1. 6-Unit System

This is a small system comprising six generators meeting a load demand of 1263 MW, and includes loss, POZs and ramp up/down limits. The characteristics of the 6-unit system are found in Ref. [13]. The optimal results obtained are presented in Table 1. The cost obtained by proposed method is 15442.8410 ($/h) and it is found to be lesser than the other methods reported in the literature while satisfying the all system constraints. From table 1, it can be concluded that the result obtained by proposed method is optimal value. For this test system, proposed FPA is compare with PSO (5), MTS (9), clonal algorithm (10), EMA (13) and BSA [14] in terms of total generation cost. Table 1 provides the comparison result, confirming that FPA converged to best fuel cost among other methods.

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**Table 1: Best and Comparison Result of the ELD in 6-Unit System.**

| Unit(MW) | PSO | MTS | Clonal Algorithm | EMA | BSA | FPA |
|---|---|---|---|---|---|---|
| $P_1$(MW) | 447.4970 | 448.1277 | 458.2904 | 447.3872 | 447.4902 | 446.8293 |
| $P_2$(MW) | 173.3221 | 172.8082 | 168.0518 | 173.2524 | 173.3308 | 173.1406 |
| $P_3$(MW) | 263.4745 | 262.5932 | 262.5175 | 263.3721 | 263.4559 | 264.3257 |
| $P_4$(MW) | 139.0594 | 136.9605 | 139.0604 | 138.9894 | 139.0602 | 139.1073 |
| $P_5$(MW) | 165.4761 | 168.2031 | 178.3936 | 165.3650 | 165.4804 | 165.7160 |
| $P_6$(MW) | 87.1280 | 87.3304 | 69.3416 | 87.0781 | 87.1409 | 86.2982 |
| $P_{LOSS}$(MW) | 12.9584 | 13.0205 | 12.655 | 12.4430 | 12.9583 | 12.4170 |
| PT(MW) | 1276.01 | 1276.0232 | 1275.655 | 1275.4430 | 1275.9583 | 1275.4170 |
| FC($/h) | 15450 | 15450.06 | 15448 | 15443.0749 | 15449.8995 | 15442.8410 |

### 4.2. 15-Unit System

This system comprises of 15 generating units with a power demand of 1263 MW, and includes loss, POZs and ramp up/down limits. The characteristics of the 15-unit system are found in Ref. [13] or presented in appendix.

The optimal results obtained are presented in Table 2. The cost obtained by proposed method is 32672.6463 ($/h) and it is found to be lesser than the other methods reported in the literature while satisfying the all system constraints. From table 2, it can be concluded that the result obtained by proposed method is optimal value. For this test system, proposed FPA is compare with PSO (5), MTS (9), clonal algorithm (10), EMA (13) and BSA [14] in terms of total generation cost. Table 2 provides the comparison result, confirming that FPA converged to best fuel cost among other methods.

**Table 2: Best and Comparison Result of the ELD in 15-Unit System Without Valve Point.**

| Unit | PSO | MTS | Clonal Algorithm | EMA | BSA | FPA |
|---|---|---|---|---|---|---|
| $P_1$(MW) | 439.1162 | 453.9922 | 441.1587 | 455.0000 | 455.0000 | 445.000 |
| $P_2$(MW) | 407.9727 | 379.7434 | 409.5873 | 380.0000 | 380.0000 | 379.998 |
| $P_3$(MW) | 119.6324 | 130.0000 | 117.2983 | 130.0000 | 130.0000 | 129.9992 |
| $P_4$(MW) | 129.9925 | 129.9232 | 131.2577 | 130.0000 | 130.0000 | 129.9999 |
| $P_5$(MW) | 151.0681 | 168.0877 | 151.0108 | 170.0000 | 170.0000 | 169.9993 |
| $P_6$(MW) | 459.9978 | 460.0000 | 466.2579 | 460.0000 | 460.0000 | 459.9991 |
| $P_7$(MW) | 425.5601 | 429.2253 | 423.3678 | 430.0000 | 430.0000 | 429.9993 |
| $P_8$(MW) | 98.5699 | 104.3097 | 99.948 | 72.0415 | 71.6368 | 60.0155 |
| $P_9$(MW) | 113.4936 | 35.0358 | 110.684 | 58.6212 | 59.0234 | 46.3866 |
| $P_{10}$(MW) | 101.1142 | 155.8829 | 100.2286 | 160.0000 | 160.0000 | 159.9903 |
| $P_{11}$(MW) | 33.9116 | 79.8994 | 32.0573 | 80.0000 | 80.0000 | 79.9966 |
| $P_{12}$(MW) | 79.9583 | 79.9037 | 78.8147 | 80.0000 | 80.0000 | 79.9985 |
| $P_{13}$(MW) | 25.0042 | 25.0220 | 23.5683 | 25.0000 | 25.0001 | 25.0009 |
| $P_{14}$(MW) | 41.4140 | 15.2586 | 40.2581 | 15.0000 | 15.0001 | 15.0131 |
| $P_{15}$(MW) | 35.6140 | 15.0796 | 36.9061 | 15.0000 | 15.0005 | 34.1611 |
| $P_{LOSS}$(MW) | 32.4306 | 31.3523 | 32.4075 | 30.6626 | 30.6609 | 25.5576 |
| PT(MW) | 2662.4 | 2661.36 | 2662.04 | 2660.6626 | 2660.6609 | 2655.5576 |
| FC($/h) | 32858 | 32716.87 | 32854 | 32704.4503 | 32704.4504 | 32672.6463 |

**Table 3: Best result of the ELD in 10-unit system with power demand=2400MW without valve point.**

| Unit | HM [16] | | MHNN [17] | | AHNN [18] | | MPSO [19] | | FPA | |
|---|---|---|---|---|---|---|---|---|---|---|
| | F | GEN | F | GEN | F | GEN | F | GEN | F | GEN |
| $P_1$(MW) | 1 | 193.2 | 1 | 192.7 | 1 | 189.1 | 1 | 189.7 | 1 | 189.7405 |
| $P_2$(MW) | 1 | 204.1 | 1 | 203.8 | 1 | 202.0 | 1 | 202.3 | 1 | 202.3427 |
| $P_3$(MW) | 1 | 259.1 | 1 | 259.1 | 1 | 254.0 | 1 | 253.9 | 1 | 253.8953 |
| $P_4$(MW) | 3 | 234.3 | 2 | 195.1 | 3 | 233.0 | 3 | 233.0 | 3 | 233.0456 |
| $P_5$(MW) | 1 | 249.0 | 1 | 248.7 | 1 | 241.7 | 1 | 241.8 | 1 | 241.8297 |
| $P_6$(MW) | 3 | 195.5 | 3 | 234.2 | 3 | 233.0 | 3 | 233.0 | 3 | 233.0456 |
| $P_7$(MW) | 1 | 260.1 | 1 | 260.3 | 1 | 254.1 | 1 | 253.3 | 1 | 253.2750 |
| $P_8$(MW) | 3 | 234.3 | 3 | 234.2 | 3 | 232.9 | 3 | 233.0 | 3 | 233.0456 |
| $P_9$(MW) | 1 | 325.3 | 1 | 324.7 | 1 | 320.0 | 1 | 320.4 | 1 | 320.3832 |
| $P_{10}$(MW) | 1 | 246.3 | 1 | 246.8 | 1 | 240.3 | 1 | 239.4 | 1 | 239.3969 |
| PT(MW) | 2401.2 | | 2399.8 | | 2400.0 | | 2400 | | 2400 | |
| FC($/h) | 488.500 | | 487.87 | | 481.700 | | 481.723 | | 481.7226 | |

### 4.3. 10-Unit System

In order to check the potential of proposed FPA on piecewise cost functions, which poses challenge to any search heuristic, ED problem comprising of 10 generators with multiple fuels is considered. The input parameters and related constraints of the aforementioned problem are detailed in Ref. [16]. Four cases were considered with input demands varying from 2400 to 2700 MW through increments of 100 MW. The best results obtained are detailed in Tables 3-6. As evident from results, FPA provided comparable results as compared to HM [16], HNN [17-18] and PSO [19] outperformed other approaches.

**Table 4: Best result of the ELD in 10-unit system with power demand=2500MW without valve point.**

| **Unit** | **HM [16]** | | **MHNN [17]** | | **AHNN [18]** | | **MPSO [19]** | | **FPA** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | F | GEN | F | GEN | F | GEN | F | GEN | F | GEN |
| $P_1$(MW) | 2 | 206.6 | 2 | 206.1 | 2 | 206.0 | 2 | 206.5 | 2 | 206.5190 |
| $P_2$(MW) | 1 | 206.5 | 1 | 206.3 | 1 | 206.3 | 1 | 206.5 | 1 | 206.4573 |
| $P_3$(MW) | 1 | 265.9 | 1 | 265.7 | 1 | 265.7 | 1 | 265.7 | 1 | 265.7391 |
| $P_4$(MW) | 3 | 236.0 | 3 | 235.7 | 3 | 235.9 | 3 | 236.0 | 3 | 235.9531 |
| $P_5$(MW) | 1 | 258.2 | 1 | 258.2 | 1 | 257.9 | 1 | 258.0 | 1 | 258.0177 |
| $P_6$(MW) | 3 | 236.0 | 3 | 235.9 | 3 | 235.9 | 3 | 236.0 | 3 | 235.9531 |
| $P_7$(MW) | 1 | 269.0 | 1 | 269.1 | 1 | 269.6 | 1 | 268.9 | 1 | 268.8635 |
| $P_8$(MW) | 3 | 236.0 | 3 | 235.9 | 3 | 235.9 | 3 | 235.9 | 3 | 235.9531 |
| $P_9$(MW) | 1 | 331.6 | 1 | 331.2 | 1 | 331.4 | 1 | 331.5 | 1 | 331.4877 |
| $P_{10}$(MW) | 1 | 255.2 | 1 | 255.7 | 1 | 255.4 | 1 | 255.1 | 1 | 255.0562 |
| PT(MW) | 2501.1 | | 2499.8 | | 2500.0 | | 2500.0 | | 2500 | |
| FC($/h) | 526.700 | | 526.13 | | 526.2300 | | 526.239 | | 526.2388 | |

**Table 5: Best result of the ELD in 10-unit system with power demand=2600MW without valve point.**

| **Unit** | **HM [16]** | | **MHNN [17]** | | **AHNN [18]** | | **MPSO [19]** | | **FPA** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | F | GEN | F | GEN | F | GEN | F | GEN | F | GEN |
| $P_1$(MW) | 2 | 216.4 | 2 | 215.3 | 2 | 215.8 | 2 | 216.5 | 2 | 209.7880 |
| $P_2$(MW) | 1 | 210.9 | 1 | 210.6 | 1 | 210.7 | 1 | 210.9 | 1 | 207.9078 |
| $P_3$(MW) | 1 | 278.5 | 1 | 278.9 | 1 | 279.1 | 1 | 278.5 | 1 | 269.9146 |
| $P_4$(MW) | 3 | 239.1 | 3 | 238.9 | 3 | 239.1 | 3 | 239.1 | 3 | 236.9782 |
| $P_5$(MW) | 1 | 275.4 | 1 | 275.7 | 1 | 276.3 | 1 | 275.5 | 1 | 263.7247 |
| $P_6$(MW) | 3 | 239.1 | 3 | 239.1 | 3 | 239.1 | 3 | 239.1 | 3 | 236.9782 |
| $P_7$(MW) | 1 | 285.6 | 1 | 286.2 | 1 | 286.0 | 1 | 285.7 | 1 | 274.3591 |
| $P_8$(MW) | 3 | 239.1 | 3 | 239.1 | 3 | 239.1 | 3 | 239.1 | 3 | 236.9782 |
| $P_9$(MW) | 1 | 343.3 | 1 | 343.5 | 1 | 342.8 | 1 | 343.5 | 1 | 402.7945 |
| $P_{10}$(MW) | 1 | 271.9 | 1 | 272.6 | 1 | 271.9 | 1 | 272.0 | 1 | 260.5767 |
| PT(MW) | 2600.0 | | 2599.8 | | 2600.00 | | 2600.00 | | 2600.0000 | |
| FC($/h) | 574.030 | | 574.26 | | 574.370 | | 574.381 | | 573.7413 | |

**Table 6: Best result of the ELD in 10-unit system with power demand=2700MW without valve point.**

| **Unit** | **HM [16]** | | **MHNN [17]** | | **AHNN [18]** | | **MPSO [19]** | | **FPA** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | F | GEN | F | GEN | F | GEN | F | GEN | F | GEN |
| $P_1$(MW) | 2 | 218.4 | 2 | 224.5 | 2 | 225.7 | 2 | 218.3 | 2 | 218.2499 |
| $P_2$(MW) | 1 | 211.8 | 1 | 215.0 | 1 | 215.2 | 1 | 211.7 | 1 | 211.6626 |
| $P_3$(MW) | 1 | 281.0 | 3 | 291.8 | 1 | 291.8 | 1 | 280.7 | 1 | 280.7228 |
| $P_4$(MW) | 3 | 239.7 | 3 | 242.2 | 3 | 242.3 | 3 | 239.6 | 3 | 239.6315 |
| $P_5$(MW) | 1 | 279.0 | 1 | 293.3 | 1 | 293.7 | 1 | 278.5 | 1 | 278.4973 |
| $P_6$(MW) | 3 | 239.7 | 3 | 242.2 | 3 | 242.3 | 3 | 239.6 | 3 | 239.6315 |
| $P_7$(MW) | 1 | 289.0 | 1 | 303.1 | 1 | 302.8 | 1 | 288.6 | 1 | 288.5845 |
| $P_8$(MW) | 3 | 239.7 | 3 | 242.2 | 3 | 242.3 | 3 | 239.6 | 3 | 239.6315 |
| $P_9$(MW) | 3 | 429.2 | 3 | 355.7 | 3 | 355.1 | 3 | 428.5 | 3 | 428.5216 |
| $P_{10}$(MW) | 1 | 275.2 | 1 | 289.5 | 1 | 288.8 | 1 | 274.9 | 1 | 274.8667 |
| PT(MW) | 2702.2 | | 2699.7 | | 2700.0000 | | 2700.0000 | | 2700.0000 | |
| FC($/h) | 625.180 | | 626.12 | | 626.240 | | 623.809 | | 622.8092 | |

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As seen in Tables 3-6, the FPA has always provided better solutions than HM [16], MHNN [17], AHNN [18] and MPSO [19]. Furthermore, it has provided solutions satisfying the load balance and power limit constraints while HM [16] and MHNN [17] do not satisfy the load balance condition. Note that the fuel types and dispatch levels from the FPA is quite different from those of other approaches.

10-unit system with multiple fuel options and valve-point effect considered. This case has been widely used as the benchmark test by a number of heuristic algorithms for purpose of performance validation and comparison in the literature. The system data, such as cost coefficients and definition of fuel types are detailed in Ref. [16]. The total demands are set to 2400 to 2700 MW through increments of 100 MW. The best solutions of generation dispatch are shown in Table 7 and the comparative results of different methods over 30 trails are presented in Table 8. The best results obtained by the proposed FPA method are compared with those obtained by other algorithms, which are CSO [15], GA [20], SADE-ALM [21] and PSO [23]. As shown in Table 8, it is clear that FPA seem to obtain much better results than other methods reported in the literatures.

**Table 7: Best result of the ELD in 10-unit system with valve-point effect.**

| Unit | 2400 MW | | 2500 MW | | 2600 MW | | 2700 MW | |
|---|---|---|---|---|---|---|---|---|
| | F | GEN | F | GEN | F | GEN | F | GEN |
| $P_1$(MW) | 1 | 189.9770 | 2 | 207.2677 | 2 | 210.1804 | 2 | 217.5543 |
| $P_2$(MW) | 1 | 201.3133 | 1 | 206.0189 | 1 | 206.5077 | 1 | 212.4541 |
| $P_3$(MW) | 1 | 255.5858 | 1 | 268.4629 | 1 | 271.5182 | 1 | 283.6590 |
| $P_4$(MW) | 3 | 233.5939 | 3 | 235.4736 | 3 | 236.9528 | 3 | 239.5028 |
| $P_5$(MW) | 1 | 239.1877 | 1 | 258.3160 | 1 | 262.8320 | 1 | 280.1443 |
| $P_6$(MW) | 3 | 232.3826 | 3 | 235.0712 | 3 | 237.6241 | 3 | 239.5047 |
| $P_7$(MW) | 1 | 252.8157 | 1 | 266.1001 | 1 | 276.0202 | 1 | 285.8161 |
| $P_8$(MW) | 3 | 234.1293 | 3 | 234.9334 | 3 | 235.7446 | 3 | 238.0254 |
| $P_9$(MW) | 1 | 322.5923 | 1 | 331.4585 | 3 | 399.4435 | 3 | 428.1905 |
| $P_{10}$(MW) | 1 | 238.4223 | 1 | 256.8978 | 1 | 263.1765 | 1 | 275.1488 |
| PT(MW) | 2400.0000 | | 2500.0000 | | 2600.0000 | | 2700.0000 | |
| FC($/h) | 481.8484 | | 526.3267 | | 573.8551 | | 622.9183 | |

**Table 8: Best and comparison result of the ELD in 10-unit system with valve-point effect (2700 MW).**

| Unit | CSO [15] | | GA [20] | | SADE-ALM [21] | | PSO [23] | | FPA | |
|---|---|---|---|---|---|---|---|---|---|---|
| | F | GEN | F | GEN | F | GEN | F | GEN | F | GEN |
| $P_1$(MW) | 2 | 218.104 | 2 | 222.010 | 2 | 218.594 | 2 | 219.066 | 2 | 217.5543 |
| $P_2$(MW) | 1 | 211.907 | 1 | 211.635 | 1 | 211.464 | 1 | 211.162 | 1 | 212.4541 |
| $P_3$(MW) | 1 | 280.657 | 3 | 283.945 | 1 | 280.657 | 1 | 279.657 | 1 | 283.6590 |
| $P_4$(MW) | 3 | 239.417 | 3 | 237.805 | 3 | 239.236 | 3 | 239.417 | 3 | 239.5028 |
| $P_5$(MW) | 1 | 279.934 | 1 | 280.448 | 1 | 279.934 | 1 | 280.096 | 1 | 280.1443 |
| $P_6$(MW) | 3 | 239.660 | 3 | 236.033 | 3 | 239.370 | 3 | 239.526 | 3 | 239.5047 |
| $P_7$(MW) | 1 | 287.727 | 1 | 292.049 | 1 | 287.727 | 1 | 287.737 | 1 | 285.8161 |
| $P_8$(MW) | 3 | 239.686 | 3 | 241.970 | 3 | 239.773 | 3 | 240.089 | 3 | 238.0254 |
| $P_9$(MW) | 3 | 427.035 | 3 | 424.201 | 3 | 427.666 | 3 | 428.173 | 3 | 428.1905 |
| $P_{10}$(MW) | 1 | 275.868 | 1 | 269.900 | 1 | 275.575 | 1 | 275.072 | 1 | 275.1488 |
| PT(MW) | 2700.0000 | | 2700.0000 | | 2700.0000 | | 2700.0000 | | 2700.0000 | |
| FC($/h) | 623.8237 | | 624.7193 | | 623.8278 | | 623.6217 | | 622.9183 | |

## V. CONCLUSION

In this paper, the proposed FPA algorithm has been successfully implemented to solve both convex and nonconvex ELD problems considering practical constraints such as ramp rate limits, valve point effects, and prohibited operating zone. In test conducted on systems with 6, 15 and 10 units. FPA has been able to find global optimum point for each run of the program. The findings considerably reveal that the FPA method has superior solution quality, computational efficiency, and robustness in achieving near global solutions compared by other methods. The results prove the robustness and effectiveness of the FPA and shows that it could be used as a reliable tool for solving the optimization problems.

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**Y. Venkata Krishna Reddy** has one year experience in teaching and research in Graduate and Post Graduate level. He has received M.Tech in the specialization of Power Systems from JNTUACE, Anantapur. Five times qualified in All India GATE entrance exam from 2012-2016. Presently he is pursuing as a Full-Time Research Scholar at S.V. University.

**Prof. M. Damodar Reddy** has 25 years of experience in teaching in Post Graduate level and 20 years of experience in Research. He has received M.Tech and Ph.D from S. V. University College of Engineering, Tirupati, India, 1992 and 2008 respectively. He has a Life Member of ISTE. Presently he is working as a Professor at S.V.University, Tirupati, India. He has published 63 Research (Journals-36, Conferences-27) Papers. Presently guiding 8 Ph.D. Scholars and 2 of them are in submission. His Research area is Power system optimization & reactive power compensation