International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-8 Issue-3, September 2019

Flower Pollination Algorithm to Solve Dynamic Economic Loading of Units with Practical Constraints

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Abstract*: Dynamic economic load dispatch (DELD) aims to obtain optimum generation schedule of the committed generating units' output over a certain timing horizon , sustaining practical restrictions and power demands in each period. Valve-point effect, the ramp up/down limits, prohibited operation zones (POZs), and power losses form the DELD as a complex, non-linear liable problem. The Flower Pollination Algorithm (FPA) is therefore anticipated in this paper to solve such a complex issue. The practicality of the proposed FPA method is assessed by conducting simulations at different load patterns on standard 5-unit and 10-unit systems for a 24-hour schedule. The FPA's simulation results are related to other previously published biography techniques. These results clearly show that the skill and robustness of the proposed FPA method to solve the non - linear DELD problem has been restricted.

***Keywords* : Dynamic economic load dispatch, Valve-point effect, Ramp up/down limits, Prohibited operation zones, Flower Pollination Algorithm.**

I. INTRODUCTION

The system which can deals with power generation, transmission and distribution in order to supply the consumer on an economical basis known as power system. Dynamic economic load dispatch (DELD) in the power system is one of the most important issues of optimization. DELD's goal is to allocate optimal generator outputs for a given variety of load demands in order to reduce overall operating costs over a given period of time, impose equality and various inequality constraints on system operation through generator ramp-rate limits. The operating cost function of generators are obtained using input-output characteristics, finally obtain quadratic function as cost function [1]. The operating cost function consist non-convexity due to steam turbines admission valves, hence the DELD problem becomes complex due to the valve-point loading in finding optimal solution. Many classical methods to evaluate the DELD problems with valve-point loading like Lagrangian relaxation [2], dynamic programming [3] and Maclaurin series [4] but these methods does not provide global optimal solution because of non-linearity and non-convexity features in the generating units. Due to the stability limits or machine components, generating units are restricted to operate certain operating zones.Therefore, due to consideration of valve point effects and POZs in objective function, DELD becomes nonconvex optimization problem.

Recently, in [5], Chaotic Quantum GA (CQGA) is used to solve the DELD problem, taking into account the effect of wind production. DE algorithms focused on solving DELD issues [6 - 9]. Other methods of empirical search include Quantum GA (QGA)[10], Artificial Bee Colony (ABC)[11], Artificial Immune System (AIS)[12], PSO[13,14], Enhanced Cross - Entropy (ECE)[15], and Multiple TS (MTS) algorithm[16] to solve DELD problems over the past decade. Hybrid methods such as hybrid swarm - based HAS [17], hybrid AIS - SQP [18], hybrid EP - SQP method [19], hybrid SOA - SQP [20], hybrid PSO - SQP [21], and AIS [22] have been found to be effective in solving complex optimization problems such as DELD.

This paper proposes an algorithm for flower pollination (FPA) to solve restricted non - convex DELD problems. Xin - She Yang recently proposed FPA [23]. This algorithm is an optimization algorithm inspired by nature based on universe pollen transfer. FPA has shown good action in solving optimization problems in various areas, as there is only one key parameter p (switch probability) that makes the algorithm faster to reach the optimal global solution. In addition, this transfer switch between local and global pollination can ensure an escape from the minimum local solution. The results of FPA method to solve DELD problem for test systems, shown that FPA can find better results compared to other exploratory algorithms.

Manuscript published on 30 September 2019
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II. DELD PROBLEM FORMULATION

The objectives function for DED problem as follows:

$$\min TC = \sum_{t=1}^{T}\sum_{i=1}^{N} C_{it}(P_{it}) \qquad (1)$$

Where C_{it} : Fuel cost of unit i at time t (in $/h), N: Number of generation units, P_{it} : Power output of ith unit at time t (in MW), T: Total number of hours.

Due to involvement of valve-point the fuel cost of a generation unit defined as:

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

The DELD problem objective function maintains the following constraints should be minimized:

2.1. Real power balance

By considering network transmission losses, the equality constraint of the given network is written as:

$$\sum_{i=1}^{N} P_{it} = P_D(t) + P_{loss}(t) \qquad t = 1,2,.....,T \qquad (3)$$

Where $P_{loss}(t)$: Total transmission loss of the system (in MW), $P_D(t)$: Total power demand of the system at time t (MW). The power loss calculated using coefficients of the B matrix as follows:

$$P_{loss}(t) = \sum_{i=1}^{N}\sum_{j=1}^{N} P_{it} B_{ij} P_{jt} \qquad t = 1,2,3,.....,T \qquad (4)$$

2.2. Generation limits of units:

$$P_i^{min} \le P_{it} \le P_i^{max} \qquad i = 1,......,N, \; t = 1,2,......,T \qquad (5)$$

Where P_i^{min} and P_i^{max} (in MW) are the minimum, maximum power outputs of ith unit.

2.3. Ramp up and ramp down constraints:

The generation unit ramp rate limits are stated as follows:

$$P_{it} - P_{it-1} \le UR_i \qquad i = 1,.....,N, \quad t = 1,2,.....,T \qquad (6)$$

$$P_{it-1} - P_{it} \le DR_i \qquad i = 1,.....,N, \quad t = 1,2,.....,T \qquad (7)$$

Where UR_i: Ramp up limit, $DR_{i:}$ Ramp down limit of the ith generator (MW/h). Due to involvement of ramp rate limits power limits can be modified as follows:

$$\max(P_i^{min}, P_{it-1} - DR_i) \le P_{it} \le \min(P_i^{max}, P_{it-1} + UR_i)$$
$$i = 1,.....,N, \quad t = 1,2,.....,T \qquad (8)$$

2.4. Prohibited operation zone limits (POZ):

Due to stability concerns or limitations of machine components generating outputs have certain delimited operation zone. The generation unit acceptable operation zone can be defined as:

$$P_{it} \in \begin{cases} P_i^{min} \le P_{it} \le P_{i,1}^{l} \\ P_{i,j-1}^{u} \le P_{it} \le P_{i,j}^{l} \qquad j = 2,3,......M_i \\ \qquad\qquad\qquad\qquad i = 1,....,N \quad t = 1,2,.....,T \\ P_{i,M_i}^{u} \le P_{it} \le P_i^{max} \end{cases} \qquad (9)$$

Where $P_{i,j}^{u}$ and $P_{i,j}^{l}$ are the upper and lower limits of the jth POZs of unit i, respectively. M_i is the number of POZs of unit i.

III. FLOWER POLLINATION ALGORITHM

3.1. Introduction

In this section, new nature inspired optimization algorithm based on flower fertilization process has been proposed and implemented on DELD problem. Xin-She Yang [23] developed FPA method in 2012. There are namely two types of fertilization 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 fertilization (10% occur) rather than using pollinators.

Cross - fertilization or self - fertilization can achieve flower fertilization. First, one is due to the pollen fertilization of a different plant flower. Second, one occurs because one flower is fertilized 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-fertilization considered, as pollen – carrying pollinators fly following Levy flights.
2. To find the local fittest, abiotic fertilization and Self-fertilization 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 fertilization, which is slightly biased toward local pollinator.

3.2. Mathematical representation of FPA

Global fittest (g_*) can be formulated using first rule, and it can be represented mathematically as Eqn. (10),

$$X_i^{t+1} = X_i^t + L(X_i^t - g_*) \qquad (10)$$

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 fertilization should be greater than zero.

Levy distribution can be represent as Eqn. (11)

$$L \sim \frac{\lambda\Gamma(\lambda) * \sin(\pi\lambda/2)}{\pi}\left(\frac{1}{S^{1+\lambda}}\right) \qquad (S \gg S_0 > 0) \qquad (11)$$

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

For the local fertilization, both Rules 2 and 3 can be signified as shown in Eqn. (12).

$$X_i^{t+1} = X_i^t + \varepsilon(X_j^t - X_k^t) \quad (12)$$

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]. In both local and global searches, flower pollination can occur. If there are two similar solutions, the search may be local; while there are two different solutions, the search will be global. The two parameters in this algorithm are population size n and probability switch (p[0,1]).

From our reproductions, found that probability switch= 0.75 for solving DELD problem. The flower pollination flowchart shown if Fig. 1, and algorithm to the proposed method discussed in below.

Implementation of Flower Pollination Algorithm:

Step 1: The algorithm begins by setting the initial population size(n), the switch probability(p), the maximum number of iterations, the search variables dimension (dim), the cost of generation coefficients, the B - matrix, the upper & lower limit and the load demand for 24 hours.

Step2: Initialize the population or solutions of flower randomly.

Sol (i, :) =Lb+ (Ub-Lb).*rand (1, dim).

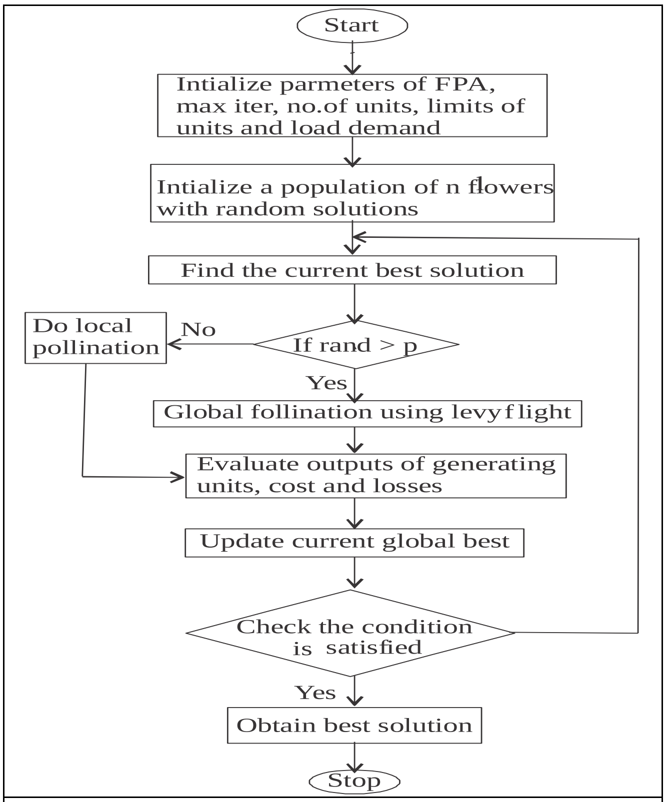

Fig. 1. Flowchart of FPA to solve ED

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 limits that are simple. If random is larger than p, use equation (10) to draw a step vector that obeys a levy distribution. Use Eqn. (11) to make the global pollination.

Step6: Draw a uniform distribution in [0, 1] randomly select j & k among all solutions if random is less than p. Use equation to do local pollination (12).

Step7: Check to see if all the restrictions are met if they are not met go to step 4. Assess new solutions (unit generation outputs, costs and losses).

Step8: Update the global fittest and its position.

Step9: Run the program up to meet the tolerance (0.00001). Display the results such as generation cost, power generations, transmission losses and total power generation for 24 hours.

IV. SIMULATION RESULTS

The FPA method is examined on two test systems with five and ten number of units in this section. MATLAB programs are executed on a PC with 4 GB RAM using MATLAB R2014a to solve DELD issues. 30 Trails are considered in order to evaluate the robustness of the proposed FPA method for each system. The number of pollens in all test systems is 40. The stop criteria are defined in this paper as reaching the tolerance of 0.00001. DELD problem is solved for three different load patterns, taking into account valve-point effects, losses and POZs, resulting in a convex quadratic programming problem.

4.1. Five unit test system

From [8], the 5-unit test system data is adapted. Valve - point loading, power losses and ramp rate limitations are considered for this test system. The total time period of one day was divided into 24 intervals and three different load patterns were considered. Table 1 presents the simulation results obtained for this test system. The proposed FPA provided a minimum cost of 42267.4315 ($) production. The test results are correlated to other methods placed in literature in terms of statistical analysis for cost over 30 runs presented in Table 2. By examining the 5 unit system results shown in Table 2, it can be noticed that the results attained by FPA method better as compare with other methods cited.

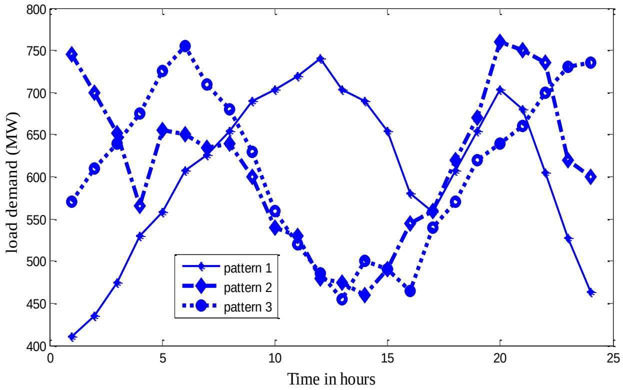

Fig. 2. Five unit test system different load patterns

From Table 2, it can be concluded that the minimum production cost of the proposed FPA is 42267.4315 ($) compared with ABC[11], AIS[12], APSO[13], HHS[17] and SOA[20] for load pattern 1.

Table 1: Best generation dispatch results obtained by FPA for 5-unit system for load pattern 1.

Hour	Pd(MW)	P1(MW)	P2(MW)	P3(MW)	P4(MW)	P5(MW)	Loss(MW)	Cost($)
1	410	10.0000	20.0000	30.0000	124.4695	229.5196	3.9891	1226.5853
2	435	34.9841	20.0000	30.0000	124.9079	229.5196	4.4116	1370.3202
3	475	10.000	20.0000	100.3506	209.8158	139.7598	4.9262	1442.5565
4	530	64.2428	94.2424	112.6730	124.9073	139.7588	5.8243	1600.8789
5	558	75.0000	104.9922	30.6560	124.9105	229.5198	7.0786	1664.8894
6	608	43.9028	20.0000	112.6735	209.8158	229.5196	7.9117	1792.0057
7	626	73.5278	98.5398	112.6735	209.8158	139.7598	8.3167	1783.7718
8	654	83.0004	113.0004	112.6737	124.9079	229.5196	9.1019	1851.3362
9	690	59.0631	89.0631	112.6735	209.8158	229.5196	10.1350	2022.8492
10	704	66.2719	96.2719	112.6735	209.8158	229.5196	10.5527	2004.3117
11	720	75.0000	104.0359	112.6735	209.8158	229.5196	11.0448	2037.9302
12	740	84.8391	114.8391	112.6735	209.8158	229.5196	11.6870	2061.3013
13	704	66.2719	96.2719	112.6735	209.8158	229.5196	10.5527	2004.3117
14	690	59.0631	89.0631	112.6735	209.8158	229.5196	10.1350	2022.8492
15	654	82.9997	112.9997	112.6721	124.9114	229.5188	9.1019	1901.3767
16	580	15.2638	20.0000	112.6735	209.8158	229.5196	7.2726	1644.1766
17	558	74.9999	104.9770	30.6684	124.9108	229.5222	7.0785	1564.8966
18	608	43.9028	20.0000	112.6735	209.8158	229.5196	7.9117	1792.0057
19	654	82.9992	112.9992	112.6736	124.9083	229.5216	9.1019	1901.3508
20	704	66.2719	96.2719	112.6735	209.8158	229.5196	10.5527	2004.3117
21	680	53.9179	83.9179	112.6735	209.8158	229.5196	9446	2029.4987
22	605	40.8304	20.0000	112.6735	209.8158	229.5196	7.8393	1781.0725
23	527	45.7974	20.0000	112.6735	124.9079	229.5196	5.8984	1449.7683
24	463	74.5609	98.5397	30.0000	124.9079	139.7598	4.7683	1313.1536
				TOTAL COST			**42267.4315**	**($)**

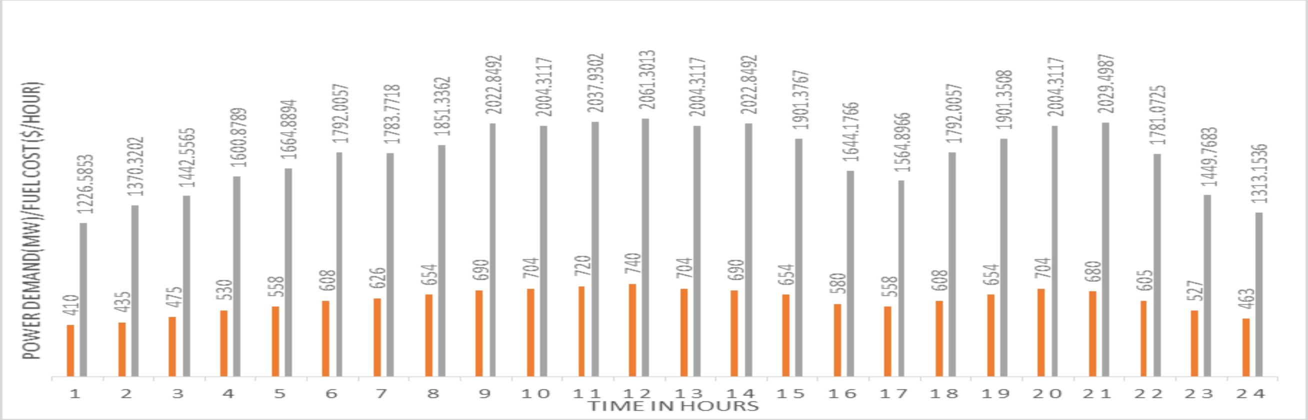

Fig. 3. Five unit test system power demands and fuel cost for load pattern 1

Figure 3 shows the fuel cost variation for each and every time interval for a day based on the power demand. The maximum load pattern 1 demand is 740 MW and 2061.3013 ($ /hr) is the corresponding cost.

Table 2: Comparison results among various stochastic methods for 5-unit system for load pattern 1

Method	Minimum Cost ($)	Average Cost ($)	Maximum Cost ($)
ABC [11]	44045.83	44064.73	44218.64
AIS [12]	44385.4300	44758.8363	45553.7707
APSO [13]	44678	NA	NA
HHS [17]	43154.3554	NA	NA
SOA [20]	42588.4156	43273.4454	43808.0937
Proposed FPA	**42267.4315**	42275.7569	42293.3243

The statistical analysis for five unit test system for different load patterns are presented in Table 3 among 30 trails run. The minimum cost for load pattern 2 using the proposed FPA method is $42915.1525, for load pattern is $42717.9027.

Table 3: Comparison results of different load patterns for 5-unit test system

Load demand	Method	Minimum Cost ($)	Average Cost ($)	Maximum Cost ($)
Pattern 1	DE [8]	43213	43813	44247
	Proposed FPA	**42267.4315**	42275.7569	42293.3243
Pattern 2	DE [8]	43979	44546	45233
	Proposed FPA	**42915.1525**	42945.0824	42983.3371
Pattern 3	DE [8]	43739	44214	45372
	Proposed FPA	**42717.9027**	42728.2132	42758.7727

4.2. Ten unit test system

From [8], the data of the 10-unit test system is adapted. Valve - point loading, power losses and ramp rate limitations are considered for this test system. The total one - day time period was divided into 24 intervals, three different load patterns were considered and shown in the appendix in Figure 4. Table 4 presents the simulation results obtained for this test system. The proposed FPA provided a minimum cost of production of $1012349.2247. The proposed FPA provided a minimum cost of $1012349.2247 production. The test results are correlated to other methods placed in literature in terms of statistical analysis for cost over 30 runs presented in Table 5. By examining the 10 unit system results shown in Table 5, it can be noticed that the results attained by FPA method better as compare with other methods cited.

Table 4: Best generation dispatch results obtained by FPA for 10-unit test system for load pattern 1

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Loss (MW)	Cost($)
1	150.0333	223.1169	171.7123	60.0000	73.1597	121.0261	129.6296	47.0000	20.0000	55.0000	14.6778	28620.8369
2	150.0993	135.1259	290.0770	60.1439	73.0211	122.8566	129.8053	86.1248	20.7641	55.0000	13.0181	30187.8034
3	150.0078	135.0000	297.1600	60.0054	222.1206	121.7187	129.8262	85.3606	20.0007	55.0000	18.2000	33432.9605
4	227.1931	307.1931	307.1990	62.5111	73.0082	128.1277	129.2217	120.0000	20.0038	55.0000	23.4539	37087.6650
5	303.2744	309.4884	295.8476	60.0195	122.7348	124.7666	129.8558	85.3320	20.5312	55.0000	26.8503	38404.2380
6	378.9547	395.8740	294.3982	60.9235	122.5616	121.5999	129.5894	85.4462	20.0000	55.0000	36.3474	41858.0376
7	380.4368	396.2324	301.1119	61.7686	223.9833	128.2965	130.0000	47.0000	20.0000	55.0000	41.8294	43592.8558
8	457.0792	396.8075	297.8649	120.6495	172.8327	122.4954	129.7238	47.2047	20.0084	55.0000	43.6661	45238.2430
9	456.5485	396.7590	300.8005	180.6963	222.8868	122.6716	129.6433	85.3484	20.0933	55.0000	46.4477	48764.2962
10	456.5298	396.7996	298.3935	299.9931	222.6081	122.4399	129.6272	120.0000	20.0024	55.0000	49.3935	52517.4395
11	456.7202	396.8433	336.2075	299.9965	222.5984	160.0000	129.6150	120.0000	20.0000	55.0000	50.9808	54575.3748
12	456.4970	459.9998	323.1328	299.9991	222.5999	160.0000	129.5906	119.9999	520574	55.0000	58.8765	56917.2625
13	456.9717	396.7667	298.4696	300.0000	222.1247	122.3566	129.8594	119.8510	20.0006	55.0000	49.4003	52545.2045
14	457.0334	396.9486	298.2654	180.7097	222.7213	124.8619	129.5493	85.4412	20.0000	55.0000	46.5306	48778.0748
15	379.8491	398.1279	322.2766	120.5122	222.2603	124.1038	129.5686	47.0123	20.0000	55.0000	42.7108	45424.1052
16	303.1416	309.7555	290.4831	60.0000	171.7888	121.9631	129.6746	119.4771	20.5667	55.0000	27.8505	40288.7611
17	301.3125	308.5684	297.7633	64.0363	121.3416	122.7987	129.2731	86.4424	20.0859	55.0000	26.6223	38532.6777
18	380.1562	309.7154	295.9273	60.0000	172.2523	122.2806	129.9608	83.6779	51.8342	55.0000	32.8046	41973.3752
19	456.7122	396.7115	297.6904	119.8792	122.9525	132.7995	129.9980	85.4925	20.0001	55.0000	41.235	45370.1946
20	456.5247	396.8086	297.9243	299.8575	222.4979	123.2010	129.5873	119.9866	20.0241	55.0000	49.4123	52525.6180
21	456.5121	396.9205	300.6491	181.2940	223.2572	122.2321	129.2994	85.2736	20.0168	55.0000	46.4548	48783.7852

22	380.1720	309.5459	312.0429	60.1373	224.2376	123.9126	129.6078	47.1002	21.1242	55.0000	34.8804	41882.2823
23	226.9360	222.2605	297.0883	60.3776	172.5195	123.0598	129.4657	47.1838	20.0662	55.0000	21.9575	34999.1380
24	150.0000	223.5795	175.0823	60.0000	220.5447	123.2751	129.1883	47.0000	20.0317	55.0000	19.5780	31982.7982
Total Cost										**1012349.2247**		

It can be concluded from Table 5 that the proposed FPA will provide a minimum cost of production of $ 1012349.2247 compared to MDE[9], ABC[11], AIS[12], ECE[13], HHS[17] and Hybrid methods[18 - 21] for load pattern 1.

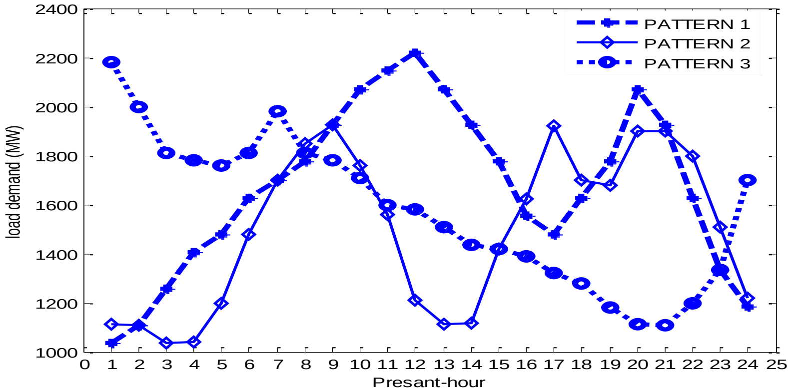

Fig. 4. Ten unit test system different load patterns

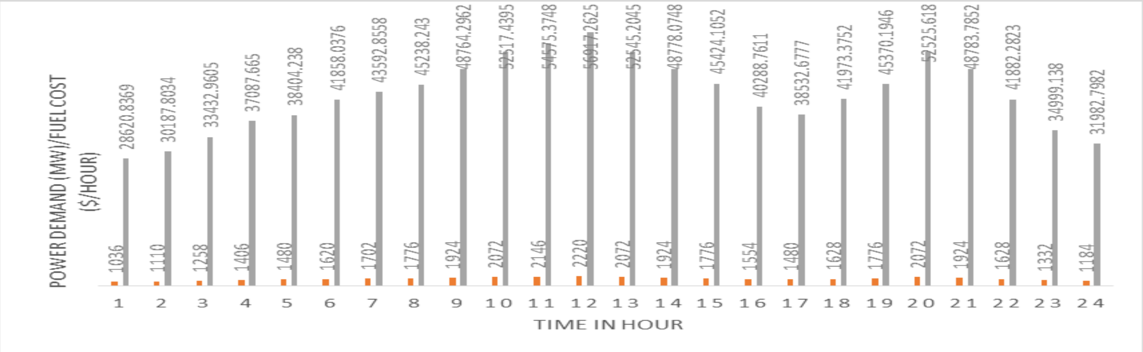

Fig. 5. Ten unit test system power demands and fuel cost for load pattern 1

Figure 5 shows the fuel cost variation for each and every time interval for a day based on the power demand. The maximum load pattern 1 demand is 2220 MW and 56917.2625 ($/hr) is the corresponding cost.

Table 5: Statistical comparison results among various methods for 10-unit system for load pattern 1

Method	Minimum Cost($)	Average Cost($)	Maximum Cost($)
MDE [9]	1034612	1033630	NA
ABC [11]	1043381	1044963	1046805
AIS [12]	1045715	1047050	1048431
ECE [15]	1022271.5793	1023334.9297	NA
HHS [17]	1019091.108	NA	NA
AIS-SQP [18]	1029900	NA	NA
EP-SQP [19]	1035748	NA	NA
SOA-SQP [20]	1021460.0101	1023840.8543	1026852.4248
PSO-SQP [21]	1027334	1028546	1033983
Proposed FPA	**1012349.2247**	1013015.8265	1013652.8705

The statistical analysis for TEN unit test system for different load patterns are presented in Table 6 among 30 trails run. The minimum cost for load pattern 2 using the proposed FPA method is $934099.7231, for load pattern 3 is $977986.4409.

Table 6: Comparison results of different load patterns for 5-unit test system

Load demand	Method	Minimum Cost ($)	Average Cost ($)	Maximum Cost ($)
Pattern 1	PSO [14]	1049167	1051725	NA

	ECE [15]	1043989.1544	1044470.0849	NA
	Proposed FPA	**1012349.2247**	1013015.8265	1013652.8705
Pattern 2	PSO [14]	957274	957732	NA
	ECE [15]	946114.2730	946782.1896	NA
	Proposed FPA	**934099.7231**	934331.0927	934501.7023
Pattern 3	PSO [14]	995177	995529	NA
	ECE [15]	988921.0673	989054.0580	NA
	Proposed FPA	**977986.4409**	978622.5485	979015.0226

V. CONCLUSION

This paper uses the Flower Pollination Algorithm (FPA) to solve the DELD problem, taking into account the effects of the valve - point and ramp - rate limits. Five and ten-unit test systems for different load patterns for 24-hour time interval demonstrated the feasibility of the proposed method. The test results show that the optimal dispatch solution obtained through the proposed FPA method is superior to other methods presented in the literature to determine the optimal solution to solve the problem of DELD. The proposed approach outperforms the methods used by MDE, ABC, ECE, PSO and Hybrid to solve DELD problems with better performance in terms of solution quality.

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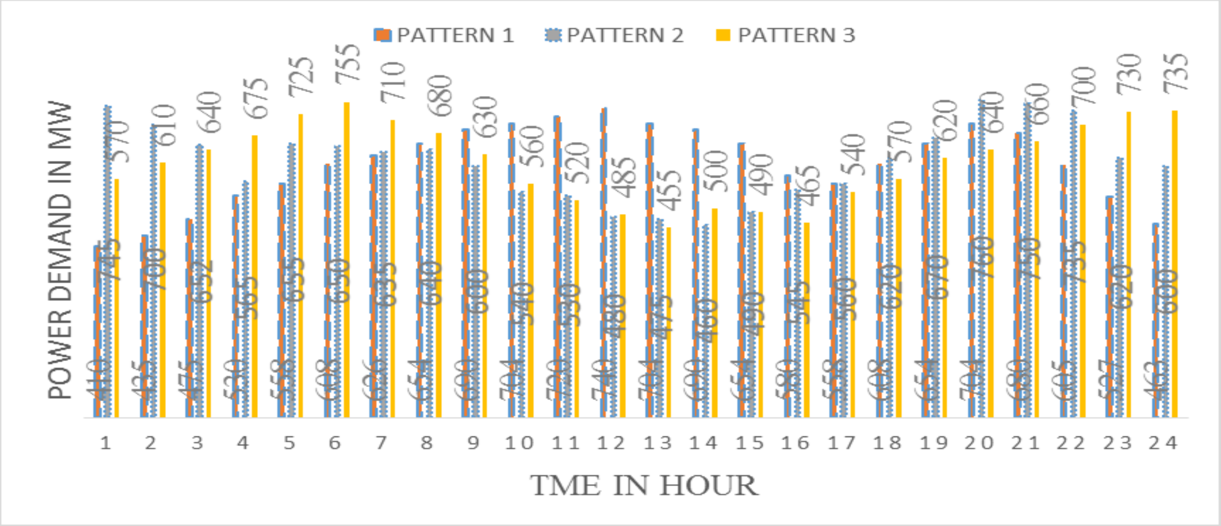
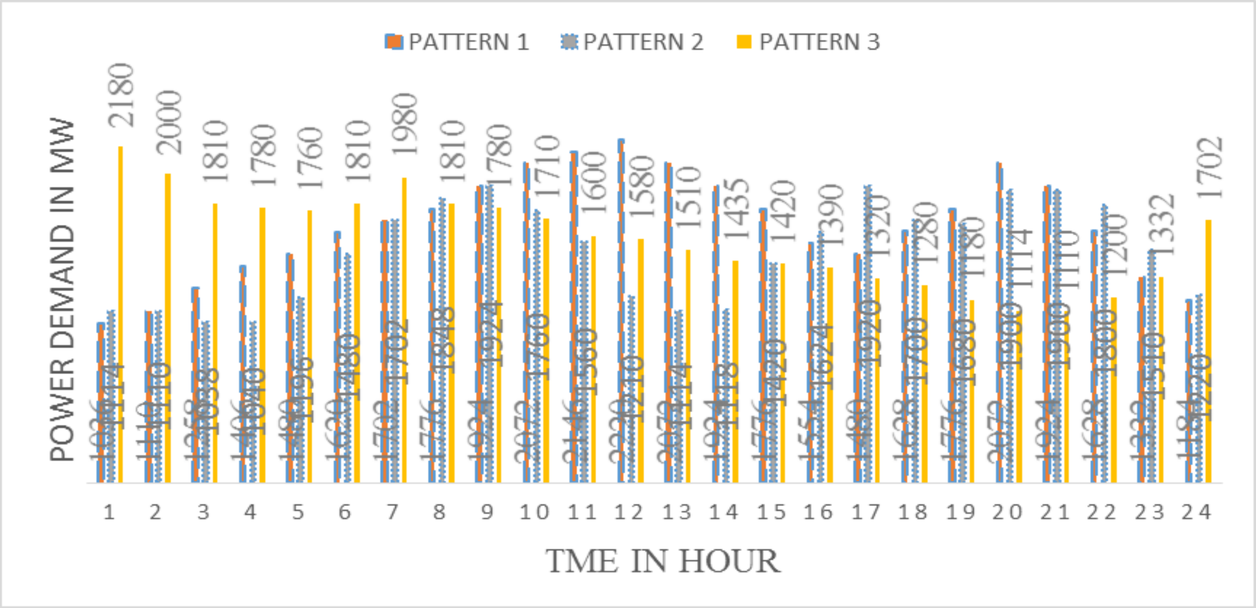
APPENDIX

APPENDIX A.1: POWER DEMAND PATTERNS FOR FIVE UNIT TEST SYSTEM



APPENDIX A.2: POWER DEMAND PATTERNS FOR TEN UNIT TEST SYSTEM



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