Front. Cur. Trends. Engg. Tech. Vol. 1(1), *pp.* 1-8 (2016)
OPEN ACCESS ISSN: 2456 - 1185
Published by ACET. Available online: www.fctet.in

An efficient algorithm for solving economic load dispatch problems with valve-point loading effects

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Abstract: The Economic Load Dispatch (ELD) problem in power generation systems is to reduce the fuel cost by reducing the total cost for the generation of electric power. This paper presents an efficient Novel TANAN's Algorithm (NTA), for solving ELD Problem with Valve-Point Loading (VPL) effects. The main objective of NTA is to minimize the total fuel cost of the generating units having quadratic cost characteristics subjected to limits on generator true power output and VPL effects. The NTA is a simple numerical random search approach by assigning a parabolic function named as TANAN function for generation output. This paper presents an application of NTA to solve ELD with VPL effect for two different IEEE standard test systems and the results from the proposed algorithm is compared with various other optimization algorithms.

Keywords: *Economic Load Dispatch, Valve-Point Loading Effect, TANAN function, Numerical Method.*

1. INTRODUCTION

Economic Load Dispatch (ELD) problem is one of the most important one in power system operation and planning. The main objective of the ELD problems is to determine the optimal combination of power outputs of all generating units so as to meet the required demand at minimum cost while satisfying the constraints. Conventionally, the cost function for each unit in ELD problems has been approximately represented by a quadratic function and is solved using mathematical programming techniques. Generally, these mathematical methods require some marginal cost information to find the global optimal solution. Unfortunately, the real-world input output characteristics of generating units are highly nonlinear and non-smooth because of prohibited operating zones, valve point loadings, and multi-fuel effects, etc. Thus, the practical ELD problem is represented as a non-smooth optimization problem with equality and inequality constraints, which directly cannot be solved by the mathematical methods. Over the past decade, in order to solve these non-smooth ELD problems, many salient methods have been developed such as hierarchical numerical method, genetic algorithm, evolutionary programming, neural network approaches, differential evolution, particle swarm optimization, and the hybrid method.

Electrical power systems are designed and operated to meet the continuous variation of power demand. In power system, minimization of the operation cost is very important. Economic Load Dispatch (ELD) is a method to schedule the power generator outputs with respect to the load demands, and to operate the power system most economically, or in other words, we can say that main objective of economic load dispatch is to allocate the optimal power generation from different units at the lowest cost possible while meeting all system constraints. The conventional methods include Newton- Raphson method, Lambda Iteration method, Base Point and Participation Factor method, Gradient method, etc. However, these classical dispatch algorithms require the incremental cost curves to be monotonically increasing or piece-wise linear. The input/output characteristics of modern units are inherently highly nonlinear (with valve-point effect, rate limits etc) and having multiple local minimum points in the cost function. Their characteristics are approximated to meet the requirements of classical dispatch algorithms leading to suboptimal solutions and therefore, resulting in huge revenue loss over the time.

Consideration of highly nonlinear characteristics of the units requires highly robust algorithms to avoid getting stuck at local optima. The classical calculus based techniques fail in solving these types of problems. In this respect, stochastic search algorithms like genetic algorithm (GA) **[**3,16**]**,

Received: 08 January 2016; Revised: 19 March 2016; Accepted: 26 March 2016; Published online: 06 April 2016

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evolutionary strategy, evolutionary programming (EP) [13], particle swarm optimization (PSO) [5, 6, 7, 8, 11] and simulated annealing (SA) [9] may prove to be very efficient in solving highly nonlinear ELD problem without any restrictions on the shape of the cost curves. Although these heuristic methods do not always guarantee the global optimal solution, they generally provide a fast and reasonable solution (sub optimal or near global optimal). The conventional optimization methods are not able to solve such problems due to local optimum solution convergence. The optimization techniques especially, Improved Dynamic Programming (IDP) [4], and Biogeography-based optimization (BBO) [2, 12] and hybrid optimization techniques like Hybrid Interior Point Assisted Differential Evolution (IPM-DE) [10], Hybrid Differential Evolution with Biogeography-Based Optimization (HDE-BBO) [1] gained incredible recognition for such types of ELD problems in last decade.

2. ECONOMIC LOAD DISPATCH WITH VALUE POINT LOADING

Economic load dispatch (ELD) is considered one of the key functions in electric power system operation. The economic load dispatch problem is commonly formulated as an optimization problem, with the aim of minimizing the total generation cost of power system but still satisfying specified constrains. The input-output characteristics (or cost functions) of a generator are approximated using quadratic or piecewise quadratic function, under the assumption that the incremental cost curves of the units are monotonically increasing piecewise-linear functions. However, real input-output characteristics display higher-order nonlinearities and discontinuities due to valve-point loading in fossil fuel burning plant. The valve-point loading effect has been modelled as a recurring rectified sinusoidal function, such as the one shown in Figure 1.

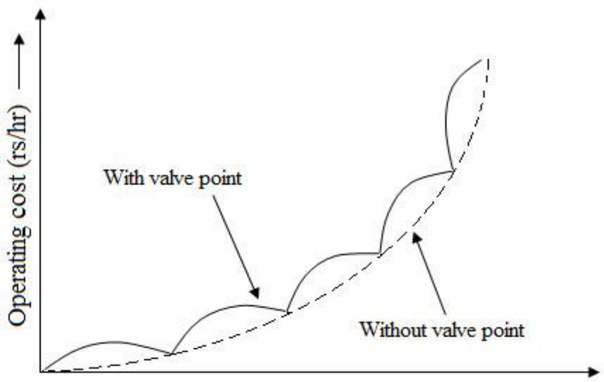

Figure 1. Operating cost characteristics with valve point loading

3. PROBLEM FORMULATION

The Economic dispatch problem is a fuel cost minimization of problem when several generators are operated to meet the required power demand. The objective function is given by

$$Minimize F_t = \sum_{i=1}^{n} F_i(P_i) \qquad (1)$$

where F_t is total fuel cost in \$/h and $F_i(P_i)$ is the fuel cost equation of the 'i'th plant expressed as follows.

$$F_i(P_i) = \sum_{i=1}^{n} a_i P_i^2 + b_i P_i + c_i \qquad (2)$$

where a_i, b_i and c_i are the fuel cost coefficients of i^{th} Generator in \$/MW^{2}h, \$/MWh, and \$/h respectively.The total fuel cost to be minimized is subject to the following constraints.

$$\sum_{i=1}^{n} P_i = P_D \qquad (3)$$

where P_i is the output power of i^{th} Generator in MW, P_D is the system power demand .

The inequality constraint is given by

$$P_i^{min} \le P_i \le P_i^{max} \qquad (4)$$

where P_i is the power output of i^{th} Generator in MW, P_i^{min} and P_i^{max} are the minimum and maximum generation limit of i^{th} Generator in MW respectively.

The valve-point loading effect has been modelled as a recurring rectified sinusoidal function, such as the one shown in Figure 1 and equation (5) represents fuel cost including valve point effects.

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i + \left| e_i \sin(f_i(P_i^{min} - P_i)) \right| \qquad (5)$$

4. NOVEL TANAN's ALGORITHM

This paper presents a novel algorithm named as Novel TANAN's Algorithm (NTA) [14, 15] for solving convex and non-convex ELD problems. NTA is a numerical random search algorithm which explores a parabolic solution to ELD problems by assigning a parabolic function named as TANAN function to each generator. In order to maintain the required power demand a dependant variable for power balance has been used in this algorithm. The TANAN function has three constant coefficients along with a random variable. All the three coefficients of TANAN function are assigned to minimum generation limits of their respective generators and

TANAN function variable is assumed to vary between 0 and 2 with an increment of 0.001 limiting the maximum iteration count to 2000. The proposed algorithm also minimises the computational time for all types of ELD problems. Since the TANAN function is a parabolic function, it has the extreme lowest point that corresponds to the optimum solution for the total fuel cost. The proposed algorithm (**Figure 2**) was programmed in MATLAB and found to exhibit better solutions with very less computational time than the other optimization techniques.

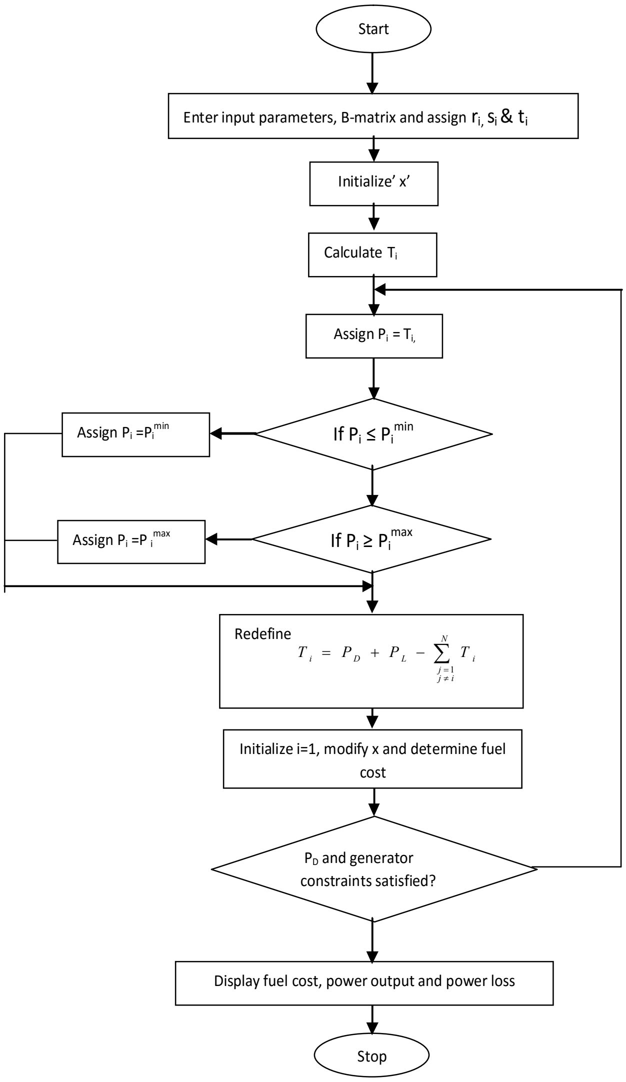

Figure 2. Flow chart for convex ELD problems

The algorithm is as follows.

First the TANAN function for each generator is defined by

$$T_i = r_i + s_i x + t_i x^2 \qquad (6)$$

A dependant variable for power balance is given by

$$T_i = P_D + P_L - \sum_{\substack{j=1 \\ j\neq i}}^{N} T_j \qquad (7)$$

Where

T_i is the TANAN function for i^{th} Generator
r_i, s_i, t_i are the coefficients of TANAN function for i^{th} Generator
x is the TANAN function variable

1. Algorithm for Convex ELD Problems

Step1: Enter input parameters, B-matrix and r_i, s_i and t_i values.
Step2: Initialize the value of x.
Step3: Calculate T_i and assign $P_i = T_i$.
Step4: If $P_i \le P_i^{min}$ then fix $P_i = P_i^{min}$ and if $P_i \ge P_i^{max}$ then fix $P_i = P_i^{max}$.
Step5: Redefine $T_i = P_D + P_L - \sum_{\substack{j=1 \\ j\neq i}}^{N} T_i$
Step6: Initialize *i* to1.
Step7: Modify 'x' value and determine the minimum fuel cost.
Step8: Repeat steps 4 to 8 for other values of *i* upto N.
Step9: Verify P_D and generator constraints, if not adjust the value of x and go to step 3.
Step10: If satisfied, notify fuel cost, power output and power loss and stop the process.

For the non-convex ELD problems, VPL effect, POZ and ramp rate limit parameters are given along with input parameters in to the proposed algorithm for convex ELD problems.

5. SIMULATION RESULTS

The NTA for ELD problem have implemented in MATLAB and it was run on a computer with Intel Core2 Duo processor, 3GB RAM memory and Windows XP operating system. IEEE standard test system datas are given in appendix.Two different IEEE standard test systems have been selected and the data for the IEEE standard test systems are given in Appendix. The proposed algorithm has been tested for the following IEEE standard test systems.

a. IEEE 13 Machine System with P_D = 1800 MW & 2520 MW
b. IEEE 40 Machine System with P_D = 10500 MW

Case-II: The lower generation limits of first three machines are assigned to one third value **(33.33%)** of their respective upper generation limits. ie. P_1^{min} =226.67 MW, P_2^{min} =120 MW and P_3^{min}=120 MW.

Case-III: The lower generation limits of first three machines are assigned to one fourth value **(25%)** of their respective upper generation limits ie. P_1^{min}=170, MW, P_2^{min}= 90 MW and P_3^{min}=90 MW.

TABLE 1

ASSUMED DEPENDANT VARIABLE WITH TANAN FUNCTION VARIABLE AND FUEL COST FOR IEEE 13 MACHINE TEST SYSTEM WITH P_D = 1800 MW BY THE PROPOSED METHOD FOR DIFFERENT CASES OF MINIMUM GENERATION LIMITS

Assumed Dependant Variable	CASE-I		CASE-II		CASE-III	
	x	$F_{T\,(\$/h)}$	x	$F_{T\,(\$/h)}$	X	$F_{T\,(\$/h)}$
T_1	0.516	18571.495	0.536	18603.675	**0.549**	**18339.885**
T_2	0.618	19180.796	0.849	19076.414	0.882	18658.403
T_3	0.618	19180.796	0.849	19076.414	0.882	18658.403
T_4	0.586	18872.285	0.728	19288.196	0.888	18588.445
T_5	0.586	18872.285	0.728	19288.196	0.888	18588.445
T_6	0.586	18872.285	0.728	19288.196	0.888	18588.445
T_7	0.586	18872.285	0.728	19288.196	0.888	18588.445
T_8	0.586	18872.285	0.728	19288.196	0.888	18588.445
T_9	0.586	18872.285	0.728	19288.196	0.888	18588.445
T_{10}	0.589	18985.430	0.728	19359.307	0.867	18647.556
T_{11}	0.589	18985.430	0.728	19359.307	0.867	18647.556
T_{12}	0.603	19128.511	0.759	19463.919	0.867	18645.580
T_{13}	0.603	19128.511	0.759	19463.919	0.867	18645.580

1. Simulation results for IEEE 13 machine test system for P_D = 1800 MW and P_D = 2520 MW with VPL effect

In IEEE 13 machine test system data, the lower generation limits of first three machines are given as zero. The proposed method has the limitation that if the minimum generation limits are zero then the coefficients r_i, s_i and t_i are be considered with some minimum value and are never to be assigned as zero. For the simulation study of IEEE 13 machine test system, the lower generation limits of first three machines are assigned as per the following three different cases for the proposed method.

Case-I: The lower generation limits of machines 1, 2 and 3 are assigned to half **(50%)** of their respective upper generation limits. ie. P_1^{min} =340 MW, P_2^{min} =180 MW and P_3^{min}=180 MW.

From the table 1, it is observed that the optimum fuel cost is **18339.885** \$/h obtained at x=0.549 and T_1 is assigned as a power balance constraint in Case-III. The individual fuel cost. From the table 2, it is observed that the optimum fuel cost is **24506.814** \$/h obtained at x=0.883 and T_1 is assigned as a power balance constraint in Case-III. The individual fuel cost. The individual fuel cost and best schedule for the proposed method were given in tables 3, 4, 5 and 6.

2. Simulation results for IEEE 40 machine test system with P_D = 10500 MW with VPL effect

For the IEEE 40 machine test system with P_D= 10500 MW, the optimum fuel cost is 122169.767, obtained at x = 0.724 with T_{10} as assumed dependant variable for power balance and the individual fuel cost and best results by the proposed method are given in table 7.

TABLE 2

ASSUMED DEPENDANT VARIABLE WITH TANAN FUNCTION VARIABLE AND FUEL COST FOR IEEE 13 MACHINE TEST SYSTEM WITH P_D = 2520 MW BY THE PROPOSED METHOD FOR DIFFERENT CASES OF MINIMUM GENERATION LIMITS

Assumed Dependant Variable	CASE-I		CASE-II		CASE-III	
	x	$F_{T\,(\$/h)}$	x	$F_{T\,(\$/h)}$	X	$F_{T\,(\$/h)}$
T_1	0.618	25142.491	0.864	24986.165	**0.883**	**24506.814**
T_2	0.618	25503.622	0.887	24793.926	0.912	25222.131
T_3	0.618	25546.068	0.887	24840.058	0.912	25189.809
T_4	0.611	25321.578	0.896	24981.335	0.968	25595.386
T_5	0.611	25321.578	0.896	24981.335	0.968	25595.386
T_6	0.611	25321.578	0.896	24981.335	0.968	25595.386
T_7	0.611	25321.578	0.896	24981.335	0.968	25595.386
T_8	0.611	25321.578	0.896	24981.335	0.968	25595.386
T_9	0.611	25321.578	0.896	24981.335	0.968	25595.386
T_{10}	0.612	25412.712	0.887	24900.556	0.962	25653.910
T_{11}	0.612	25412.712	0.887	24900.556	0.962	25653.910
T_{12}	0.618	25482.181	0.886	24880.125	0.962	25662.388
T_{13}	0.618	25482.181	0.886	24880.125	0.962	25662.388

TABLE 3

GENERATION LIMITS AND INDIVIDUAL FUEL COST FOR IEEE 13 MACHINE TEST SYSTEM WITH P_D = 1800 MW BY THE PROPOSED METHOD FOR DIFFERENT CASES OF MINIMUM GENERATION LIMITS

Unit	P_i^{min} (MW)	P_i^{max} (MW)	Fuel Cost (\$/h) case-I	Fuel Cost (\$/h) case-II	Fuel Cost (\$/h) case-III
1	0	680	2016.283	3504.784	4249.367
2	0	360	3037.361	2277.186	1688.045
3	0	360	3035.361	2275.186	1686.045
4	60	180	1132.272	1129.944	1150.192
5	60	180	1132.272	1129.944	1150.192
6	60	180	1132.272	1129.944	1150.192
7	60	180	1132.272	1129.944	1150.192
8	60	180	1132.272	1129.944	1150.192
9	60	180	1132.272	1129.944	1150.192
10	40	120	802.628	804.977	806.140
11	40	120	802.628	804.977	806.140
12	55	120	1041.801	1078.451	1101.497
13	55	120	1041.801	1078.451	1101.497
Total Cost			18571.495	18603.675	**18339.885**

TABLE 4

GENERATION LIMITS AND INDIVIDUAL FUEL COST FOR IEEE 13 MACHINE TEST SYSTEM WITH P_D = 2520 MW BY THE PROPOSED METHOD FOR DIFFERENT CASES OF MINIMUM GENERATION LIMITS

Unit	P_i^{min} (MW)	P_i^{max} (MW)	Fuel Cost (\$/h) case-I	Fuel Cost (\$/h) case-II	Fuel Cost (\$/h) case-III
1	0	680	4036.124	4242.098	5765.351
2	0	360	3488.996	3140.841	2282.616
3	0	360	3439.141	3138.841	2280.616
4	60	180	1559.516	1592.891	1559.516
5	60	180	1559.516	1592.891	1559.516
6	60	180	1559.516	1592.891	1559.516
7	60	180	1559.516	1592.891	1559.516
8	60	180	1559.516	1592.891	1559.516
9	60	180	1559.516	1592.891	1559.516
10	40	120	1138.339	1141.394	1138.339
11	40	120	1138.339	1141.394	1138.339
12	55	120	1272.228	1272.228	1272.228
13	55	120	1272.228	1272.228	1272.228
Total Cost			25142.491	24793.926	**24506.814**

TABLE 5
BEST RESULTS FOR IEEE 13 MACHINE TEST SYSTEM WITH P_D= 1800 MW WITH VPL EFFECT BY THE PROPOSED METHOD

Parameter	**Simulation output (case III)**
X	**0.549**
P_1(MW)	449.207
P_2(MW)	166.536
P_3(MW)	166.536
P_4(MW)	111.024
P_5(MW)	111.024
P_6(MW)	111.024
P_7(MW)	111.024
P_8(MW)	111.024
P_9(MW)	111.024
P_{10}(MW)	74.016
P_{11}(MW)	74.016
P_{12}(MW)	101.772
P_{13}(MW)	101.772
Total power (MW)	1800
Total fuel cost ($/h)	**18339.885**
Average Simulation time (sec)	0.27

TABLE 6
BEST RESULTS FOR IEEE 13 MACHINE TEST SYSTEM WITH P_D= 2520 MW WITH VPL EFFECT BY THE PROPOSED METHOD

Parameter	**Simulation output (case III)**
X	**0.883**
P_1(MW)	629.133
P_2(MW)	239.642
P_3(MW)	239.642
P_4(MW)	159.761
P_5(MW)	159.761
P_6(MW)	159.761
P_7(MW)	159.761
P_8(MW)	159.761
P_9(MW)	159.761
P_{10}(MW)	106.508
P_{11}(MW)	106.508
P_{12}(MW)	120.000
P_{13}(MW)	120.000
Total power (MW)	2520
Total fuel cost ($/h)	**24506.814**
Average Simulation time (sec)	0.27

TABLE 7

GENERATOR LIMITS, POWER OUTPUTS AND INDIVIDUAL FUEL COST FOR IEEE 40 MACHINE TEST SYSTEM WITH P_D = 10500 MW WITH VPL EFFECT BY THE PROPOSED METHOD

Generator Unit	**P_i^{min} (MW)**	**P_i^{max} (MW)**	**Optimal Generation (MW)**	**Fuel Cost ($/h)**
1	36	114	79.360	672.254
2	36	114	79.360	672.254
3	60	120	120.000	1449.972
4	80	190	176.355	2104.586
5	47	97	97.000	775.103
6	68	140	140.000	1573.162
7	110	300	242.488	2271.999
8	135	300	297.599	2907.938
9	135	300	297.599	2927.392
10	130	300	286.577	4916.528
11	94	375	207.217	3529.435
12	94	375	207.217	3551.390
13	125	500	275.554	4677.490
14	125	500	275.554	4767.291
15	125	500	275.554	4787.204
16	125	500	275.554	4787.204
17	220	500	484.976	5249.290
18	220	500	484.976	5241.431
19	242	550	533.474	5790.399
20	242	550	533.474	5790.379
21	254	550	550.000	5333.910
22	254	550	550.000	5333.910
23	254	550	550.000	5316.630
24	254	550	550.000	5316.630
25	254	550	550.000	5544.245
26	254	550	550.000	5544.245
27	10	150	22.044	1381.797
28	10	150	22.044	1381.797
29	10	150	22.044	1381.797
30	47	97	97.000	775.103
31	60	190	132.266	1101.381
32	60	190	132.266	1101.381
33	60	190	132.266	1101.381
34	90	200	198.399	1887.477
35	90	200	198.399	1830.716
36	90	200	198.399	1830.716
37	25	110	55.111	680.402
38	25	110	55.111	680.402
39	25	110	55.111	680.402
40	242	550	509.651	5522.748
Total Generation & Total Cost			10500	**122169.767**
Average simulation time (sec)				0.39

TABLE 8

COMPARISON TABLE FOR POWER OUTPUT AND FUEL COST OF IEEE13 MACHINE TEST SYSTEM WITH P_D=1800 MW BY THE PROPOSED METHOD WITH AGA, HGA, SGA, AHSGA, IGA, PSO-SQP, HDE, IFEP AND ICA-PSO ALGORITHMS

ALGORITHMS	Total Cost($/h)
AGA*	18078.39
HGA*	18077.49
SGA*	18083.29
AHSGA*	18078.39
IGA*	18063.58
PSO-SQP*	17969.79
HDE*	17975.73
IFEP*	17994.07
ICA-PSO*	17960.37
Proposed Method	**18339.885**

TABLE 9

COMPARISON TABLE FOR POWER OUTPUTS AND TOTAL FUEL COST FOR IEEE 13 MACHINE TEST SYSTEM WITH P_D= 2520 MW INCLUDING VPL EFFECT BY THE PROPOSED METHOD WITH GA, PSO-SQP, DE, ICA-PSO AND SA METHODS

Parameter	GA*	PSO-SQP*	DE*	ICA-PSO*	SA*	NTA
P_1(MW)	628.32	628.32	628.31	628.3	628.31	629.1
P_2(MW)	356.49	299.05	299.19	299.1	299.19	239.6
P_3(MW)	359.43	298.96	299.19	294.5	299.19	239.6
P_4(MW)	159.73	159.46	159.73	159.7	159.73	159.7
P_5(MW)	109.86	159.14	159.73	159.7	159.73	159.7
P_6(MW)	159.73	159.27	159.73	159.7	159.73	159.7
P_7(MW)	159.63	159.53	159.73	159.7	159.73	159.7
P_8(MW)	159.73	158.85	159.73	159.7	159.73	159.7
P_9(MW)	159.73	159.78	159.73	159.7	159.73	159.7
P_{10}(MW)	77.31	110.96	77.399	114.8	77.399	106.5
P_{11}(MW)	75.00	75.000	77.399	77.4	77.399	106.5
P_{12}(MW)	60.00	60.000	92.399	55	87.684	120.0
P_{13}(MW)	55.00	91.640	87.684	92.4	92.399	120.0
Total Fuel Cost ($/h)	24398.2	24261.05	24169.91	24178.6	24169.91	**24506.8**

TABLE 10

COMPARISON TABLE FOR POWER OUTPUTS AND TOTAL FUEL COST FOR IEEE 40 MACHINE TEST SYSTEM WITH P_D= 10500 MW INCLUDING VPL EFFECT BY THE PROPOSED METHOD WITH GA, PSO-SQP, DE, ICA-PSO AND SA METHOD

ALGORITHMS	Total Cost($/h)
ICA-PSO*	121413.20
DE*	121416.29
NPSO-LRS*	121664.43
TM*	122477.78
MPSO*	122252.26
PSO-SQP*	122094.67
IFEP*	122624.35
SA-PSO*	121430.00
SOH-PSO*	121501.14
Proposed Method	**122169.767**

Table 8 to table 10 presents the comparison of fuel cost for the proposed method for IEEE13 machine test system with VPL effect (PD = 1800 MW & 2520 MW) and IEEE40 machine test system with VPL effect (PD = 10500 MW) respectively with various optimization algorithms.

6. CONCLUSION

The ELD problems including valve point loading effects are presented in this chapter and the results from the proposed method are compared with various optimization algorithms.

a. For IEEE 13 machine test system with P_D = 1800 MW and P_D = 2520 MW, the total fuel cost by the proposed method is inferior to all other optimization methods as given in the comparison tables 8 and 9. Further fine tuning is needed to improve the solution of the proposed system.
b. For IEEE 40 machine test system with P_D = 10500 MW, the total fuel cost by the proposed method is less than TM, MPSO and IFEP methods and it is higher than other optimization methods as given in comparison table 10.

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