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Opposition Based Differential Evolution Algorithm for Dynamic Economic Emission Load Dispatch (EELD) with Emission Constraints and Valve Point Effects

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Abstract – Optimal Power dispatch is the short-term decision of the optimal output of a number of power generation facilities, to meet the system demand, with the objective of Power dispatching at the lowest possible cost, subject to transmission lines power loss and operational constraints. The operational constraint includes power balance constraint, generator limit constraint, and emission dispatch constraint and valve point effects. In this paper, Opposition based Differential Evolution Algorithm (ODEA) has been proposed to handle the objective function and the operational constraints simultaneously. Furthermore, the valve point loading effects and transmission lines power loss are also considered for the efficient and effective Power dispatch. The ODEA has unique features such as self tuning of its control parameters, self acceleration and migration for searching. As a result, it requires very minimum executions compared with other searching strategies. The effectiveness of the algorithm has been validated through four standard test cases and compared with previous studies. The proposed method out performs the previous methods.

Keywords: Economic load dispatch, Economic emission dispatch, Differential evolution, Optimization, Valve point effect, etc.

1. Introduction

Power systems need to be operated economically to make electrical energy cost-effective to the consumer in the face of constantly rising prices of fuels, wages, salaries, etc. Optimal dispatchingis the process of allocation of generation among different generating units. Classical optimization techniques like direct search [1, 2] and gradient methods fail to give the global optimum solution. Normally, for any power generation industry, minimization of the emission of pollutants has been considered as an additional objective along with the minimization of the generation cost. An approach based on strength Pareto evolutionary algorithm that inherits a diversity-preserving mechanism for environmental/economic dispatch problem has been suggested to obtain Pareto optimal solutions in [3]. The Pareto optimal solution for environmental/economic dispatch problem has been suggested with inheriting a diversity-preserving mechanism [4] and has been compared with various algorithms involving non-dominated sorting genetic algorithm, niched Pareto genetic algorithm and strength Pareto evolutionary algorithm in [5].

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In the recent past decades, the economic dispatch has been carried out through the population based optimization algorithms such as Evolutionary Programming [5], Genetic Algorithm [6], Particle Swarm Optimization [7] and Tabu Search [8]. Though the algorithms produced optimal dispatch, they handled only the fuel cost minimization and evade the emission of pollutants. The hybrid optimization algorithm, which is the combination of differential evolution (DE) and Biogeography-based Optimization(BBO) algorithm [9], has been proposed to solve complex Economic Emission Load dispatch (EELD) problems of thermal generators of power systems. The equal embedded algorithm (EEA) for economic dispatch problem with the presence of transmission losses has been presented in [10]. A modified objective function for obtaining the best compromise solution of EELD problem based on biogeography has been developed in [11]. In [12], a multi-objective directed bee colony optimization algorithm (MODBC) is presented for solving a multi-objective EELD problem with the presence of both equality and inequality constraints.

With the advancements of optimization algorithms and the complexity involved in the previous practices, more dynamic hybrid techniques and advanced optimization techniques have been employed for EELD problem. Combined bacterial foraging and Nelder-Mead method (called BF-NM algorithm) [13], Parallelized particle swarm optimization algorithm (PSPSO) [14], non-dominated sorting QOTLBO [15], h-PSO [16] (MSFLA) with genetic algorithm (GA) [17], Interactive Honey Bee

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Mating Optimization (IHBMO) [18] and trust region algorithm [19] were practiced for EELD problem in recent times.

Opposition based Differential Evolution (ODE) [20] algorithm is a recent evolutionary algorithm with enhanced features such as self acceleration, self migration and assured optimal search with least population size. The efficiency of the algorithm can be well proven by applying into complex and/or large problems. The effectiveness of the ODE algorithm has been proven by comparing it with other soft computing techniques after implementing to standard benchmark problems in [21, 22]. In this paper, ODE algorithm has been proposed to solve EELD problem with the presence of operational constraints. The effectiveness of the algorithm has been validated through three standard test cases and compared with previous studies.

2. Search Strategy through ODE

In general, evolutionary optimization methods start with some candidate solutions (initial population) and try to improve them toward some optimal solution(s). The process of searching terminates when some predefined criteria are satisfied. In the absence of a priori information about the solution, it usually starts with a random guess. The computation time, among others, is related to the distance of these initial guesses from the optimal solution. It can improve the chance of starting with a closer (fitter) solution by simultaneously checking the opposite solution. By doing this, the fitter one (guess or opposite guess) can be chosen as an initial solution. In fact, according to probability theory, 50% of the time a guess is farther from the solution than its opposite. So, starting with the closer of the two guesses (as judged by its fitness) has the potential to accelerate convergence. The same approach can be applied not only to initial solutions but also continuously to each solution in the current population. Similar to all population-based optimization algorithms, two main steps are distinguishable for DE, namely population initialization and producing new generations by evolutionary operations such as mutation, crossover, and selection. It has been enhanced using the opposition-based optimization concept. The classical DE is chosen as a parent algorithm and the proposed opposition-based schemes are embedded in DE to accelerate its convergence speed. The generalized flowchart for the ODE algorithm is given in Fig. 1.

2.1 Opposition-based population initialization

In absence of a priori knowledge, random number generation is generally the only choice to create an initial population. But as mentioned before, by utilizing OBO fitter starting candidates could be obtained even when there is no a priori knowledge about the solution(s). Block (1) from Fig. 1 shows the implementation of opposition-based population initialization.

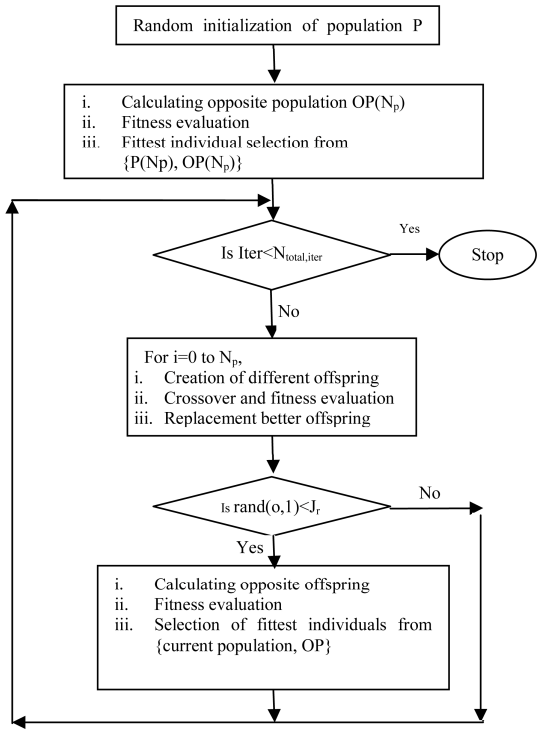


Fig. 1. Flowchart of the Generalized ODE algorithm

2.2 Opposition-based generation jumping

By applying a similar approach to the current population, the evolutionary process can be forced to jump to a fitter generation. Based on a jumping rate Jr(i.e. jumping probability), after generating new populations by mutation, crossover, and selection, the opposite population is calculated and the Npfittest individuals are selected from the union of the current population and the opposite population. As a difference to opposition based initialization, it should be noted here that in order to calculate the opposite population for generation jumping, the opposite of each variable is calculated dynamically.

By staying within variables' static boundaries, it is possible to jump outside of the already shrunken search space and loose the knowledge of the current reduced space (converged population). Hence, the opposite points can be calculated by using variables' current interval in the population which is, as the search does progress, increasingly smaller than the corresponding initial range. Block (2) from Fig. 1 indicates the implementation of opposition-based generation jumping.

3. Problem Formulation

Generators in system operation studies are represented by input/output cost curves. It is the standard industrial

practice that the fuel cost of generator is represented by polynomial for Economic Dispatch Computation (EDC). The key issue is to determine the degree and the coefficients such that the error between the polynomial and test data is sufficiently low. In this condition, if the valve-point effects of thermal units are considered in the proposed Economic and emission Power dispatch (EELD) problem, a non-smooth and non-convex cost function will be obtained. For this purpose, ramp rate limit, transmission line losses, maximum emission limit for specific power plants or total power system and dynamic loading constraints are considered in the optimization problem. Traditionally, in the EELD, the fuel cost and emission cost function for each generator has been approximately represented by a single quadratic function.

3.1 Fuel cost function

The generated real power P_{gi} accounts for the major influence on F_{gi}. The individual real generations are raised by increasing the prime mover torques, and this requires a cost of increased expenditure of fuel. The fuel cost function is generally considered to be a square cost function. Further, in order to satisfy the power balance equation under variable demand it is necessary to modify the switch status of the steam valves of the turbines. Therefore, it is essential to consider valve point effect in the fuel cost function. The total system fuel cost is the sum of the individual unit fuel costs. The fuel cost function along with valve point effect is expressed as Eq. (1),

$$F_{g,cost} = \sum_{gi=1}^{Ng}[\left(a_{gi} + b_{gi}P_{gi} + c_{gi}P_{gi}^2\right) + |\, e_{gi} * sin(f_{gi}\left(P_{gi,min} - P_{gi}\right)|] \tag{1}$$

3.2 Emission function

The generating stations based on fossil-fuel emit nitrogen oxides (NOx) and sulfur oxides (SOx) during operation. The environmental protection agency highly recommends reduction in emission of these gases produced by the utilities. For environmental emissions, the generators should pay a penalty; it has been represented in terms of real power generated. The emission function is expressed as (2),

$$F_{g,emission} = \sum_{gi=1}^{Ng}[\left(\alpha_{gi} + \beta_{gi}P_{gi} + \gamma_{gi}P_{gi}^2\right) + |\, \zeta_{gi} * sin\left(\lambda_{gi}\left(P_{gi,min} - P_{gi}\right)|\right]] \tag{2}$$

3.3 Problem constraints

The economic power system operation needs to satisfy the following practical constraints.

3.3.1 Power balance constraint

Power balance constraint of the fuel cost function is the equality constraint; it reflects the match between supply system and load demand. It is well proven that cost function is not affected by the reactive power demand. Therefore, the full attention is given to the real power balance in the system and is expressed as,

$$\sum_{gi=1}^{Ng} P_{gi} - P_{Demand} - P_{tr,loss} = 0 \tag{3}$$

$P_{tr,loss}$ is the transmission loss. It can be calculated using B loss co-efficients, it is expressed as,

$$P_{tr,loss} = \sum_{gj=1}^{ng}\sum_{gk=1}^{ng} P_{gj}B_{gj,gk}P_{gk} + \sum_{gj=1}^{ng} B_{0,gj}P_{gj} + B_{00} \tag{4}$$

3.3.2 Generator limit constraint

The maximum active power generation of a source is limited again by thermal consideration and also minimum power generation is limited by the flame instability of a boiler. If the power output of a generator for optimum operation of the system is less than a pre-specified value $P_{gi,min}$, the unit is not put on the bus bar because it is not possible to generate that low value of power from the unit. Hence, the generator power P_{gi} cannot be outside the range stated by the inequality constraint as,

$$P_{gi,min} \le P_{gi} \le P_{gi,max} \tag{5}$$

3.3.3 Ramp rate constraint

The generation power of the generation plants has to be limited by their previous hour generation and it is expressed as (6) and (7),

$$P_{gi}^0 - P_{gi} \le D_{gi} \tag{6}$$

$$P_{gi} - P_{gi}^0 \le U_{gi} \tag{7}$$

3.4 Economic Emission Load Dispatch (EELD)

The single objectives expressed in Eqs. (1) and (2) are brought into multi-objective function through the Prize Penalty Factor (PPF_{gi}). The mathematical formulation of the multi-objective optimization problem combining minimization of fuel cost and emission function for the 'Ng' number of generators present in the system is expressed as (8),

$$Minimize\ F_{eeld} = \sum_{gi=1}^{Ng}\left[F_{gi,cost} + PPF_{gi} * F_{gi,emission}\right] \tag{8}$$

The prize penalty factor [13] for the individual generating plants has been calculated using the expression (9) shown below,

$$PPF_{gi} = \frac{\sum_{gi=1}^{Ng}[\left(a_{gi} + b_{gi}P_{gi,max} + c_{gi}P_{gi,max}^2\right)}{\sum_{gi=1}^{Ng}[\left(\alpha_{gi} + \beta_{gi}P_{gi,max} + \gamma_{gi}P_{gi,max}^2\right)} \quad (9)$$

4. Proposed ODE Algorithm

The search strategy through ODE starts from identifying the number of generating units with their minimum and maximum capacity of generation. The complete flowchart for the EELD through ODE is shown in Fig. 2.

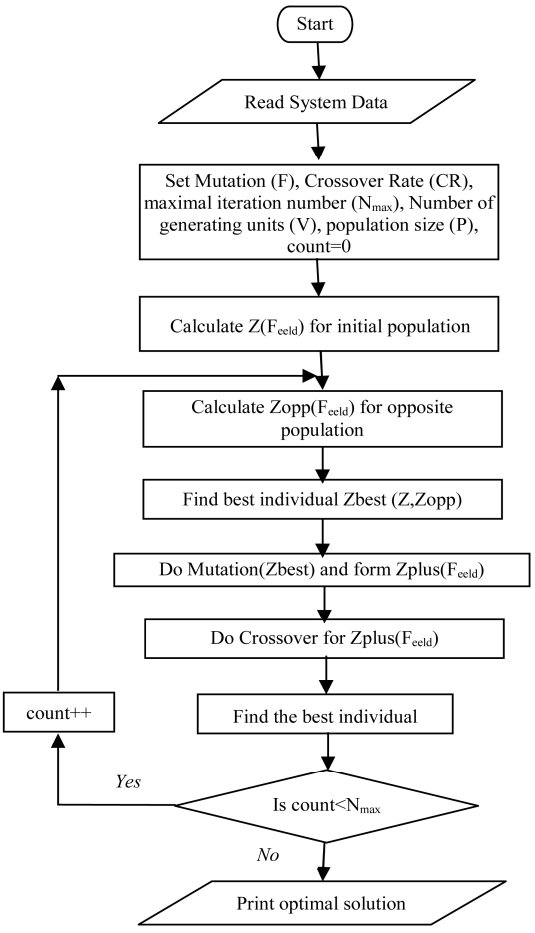


Fig. 2. Flowchart for EELD through ODE

The pseudo code of the proposed algorithm for the EELD problem is given below,

Set Mutation (F), Crossover Rate (CR), maximal iteration number (N_{max}), Number of generating units (V), population size (P), count=0
Z(P,V)=random(V_{min},V_{max}) // Initial Population
Obj(Z(P))
// Calculate the cost F_{eeld} for all population
Z_{opp}(P,V)= Opposite (Z(P,V))
//Opposite population
Obj(Z_{opp}(P))
//Calculate the cost F_{eeld} for all population
Z_{best}(P)=best(Obj(Z(P)),Obj(Z_{opp}(P)))
//Findbest individual
do (count<N_{max})
{
//Mutation operation for the Z_{best}
Z_{plus}(P,V)=Mutation (Z_{best}(P,V)))
// Crossover operation for the Z_{best}
Z(P,V)=COR(Z,Z_{plus})
//Opposition based Generation Jumping and selection best individual for next iteration
Z_{opp}(P,V)=Opposite(Z(P,V))
Z(P,V)=best(Obj(Z(P)),Obj(Z_{opp}(P)))
}

5. Simulation Results

The proposed ODE algorithm is applied to the four standard test cases of different in size such as 3, 6, 13 and 40 generators to investigate the effectiveness of the algorithm. The details of the input characteristics of the test cases are shown through Table 1. The load pattern for the 24hr is taken from the literature [23]. The control parameters of ODE are set Crossover Rate (CR) as 0.5and Mutation as (F) as 0.7.

5.1 Test case 1

This test case has 3 generators with a base load of 210MW and the fuel cost co-efficient and B-loss co-efficient are detailed in [10]. As per the ODE, the 3 variables considered for number of generators and the ranges of the variables are picked from their minimum and maximum generating range of the generating units

Table 1. Input characteristic of Test Cases

Test cases	Inputs						
	No. of Gen.	Base Load (MW)	Fuel cost co-efficient	Emission co-efficient	B-loss co-efficient	Valve point effects	Cited in
Test case 1	3	210	Provided	-	Provided	-	[10]
Test case 2	6	283	Provided	Provided	Provided	-	[11,14] and [15]
Test case 3	13	1800	Provided	Provided	Provided	Provided	[11] and [15]
Test case 4	40	10500	Provided	Provided	Provided	Provided	[11,14] and [15]

Table 2. Simulation results of Test Case 1

Parameters	Methods				
	Lambda Iterative method	GA	PSO	Ref. [10]	Proposed ODE
P_{g1} (MW)	73.52	73.83	73.81	73.97	73.72
P_{g2} (MW)	69.50	69.95	69.94	69.66	70.81
P_{g3} (MW)	75.78	75.02	74.99	75.16	75.46
Loss (MW)	8.81	8.87	8.81	8.80	8.80
Fuel cost($/hr)	3163.9	3163.63	3162.93	3163.69	3161.41

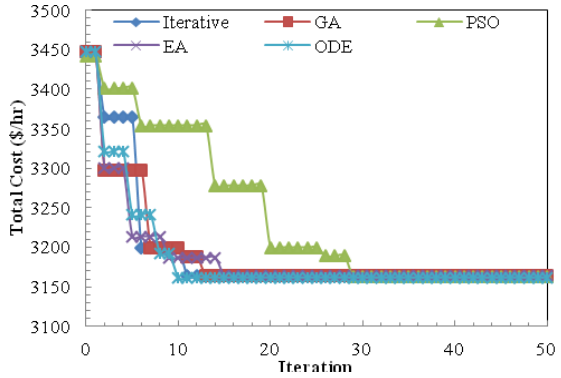


Fig. 3. Convergence characteristic of optimization methods for Test Case 1

Table 3. Fuel cost of Test Case 1 at 24 hour load span

Hr.	Load (MW)	P_{g1} (MW)	P_{g2} (MW)	P_{g3} (MW)	Loss (MW)	Fuel Cost ($/hr)
1	199	76.27	86.14	46.23	9.64	3032.73
2	189	98.08	47.20	51.84	8.12	2924.97
8	168	69.80	57.04	47.65	6.49	2642.06
4	157	54.26	52.52	57.08	6.86	2506.97
5	147	50.41	56.14	47.05	6.61	2383.04
6	206	104.88	45.12	64.30	8.39	3144.71
7	199	76.27	86.14	46.23	9.64	3032.73
8	195	83.21	75.38	45.13	8.72	2989.29
9	210	73.72	70.81	75.46	8.80	3161.41
10	231	91.22	73.56	77.83	11.61	3447.79
11	179	50.67	46.71	91.74	10.12	2782.88
12	189	98.08	47.20	51.84	8.12	2924.97
13	168	69.80	57.04	47.65	6.49	2642.06
14	199	76.27	86.14	46.23	9.64	3032.73
15	206	104.88	45.12	64.30	8.39	3144.71
16	168	69.80	57.04	47.65	6.49	2642.06
17	189	98.08	47.20	51.84	8.12	2924.97
18	157	54.26	52.52	57.08	6.86	2506.97
19	252	83.21	59.21	123.07	13.49	3745.40
20	231	91.22	73.56	77.83	11.61	3447.79
21	210	73.72	70.81	75.46	8.80	3161.41
22	189	98.08	47.20	51.84	8.12	2924.97
23	147	50.41	56.14	47.05	6.61	2383.04
24	147	50.41	56.14	47.05	6.61	2383.04

referring the load data. The population size and iteration number are set as 10 and 50 correspondingly. After the successful execution of the ODE with setting the Eq. (8) as the fitness function, the total fuel cost has been optimized to 3163.694 $/hr. The obtained result has been compared with the results in the literature in Table 2. From the table results, it is confirmed that the proposed method outperforms the other optimization methodsand produced much more optimum result. Furthermore, with the special characteristics (generation jumping) of ODE, the optimum solution has been reached much earlier compared with the other methods. The convergence characteristics of the different methods for the Test Case 1 have been shown through the Fig. 3.

In order to verify the dynamic capability of the algorithm, it has been applied to 24 hours daily load pattern described in [24]. The fuel cost at the end of defined iterations at different timings is shown through the Table 3.

5.2 Test case 2

The next test case considered for implementation is the IEEE 30-bus with 6 generators with a base load of 283MW. The fuel cost co-efficient, emission co-efficient and B-loss co-efficient of the test case are detailed in [11, 14] and [15].

The population size and iteration are set as 10 and 50 respectively. The proposed ODE tunes for the optimum with setting the Eq. (1), Eq. (2) and Eq. (8) as the fitness function with considering fuel cost reduction, emission

Table 4. Prize Penalty factor of generating units of Test Case 2

Gen. Unit	P_{g1}	P_{g2}	P_{g3}	P_{g4}	P_{g5}	P_{g6}
PPF	23.18	32.70	20.42	25.53	10.93	12.01

Table 5. Simulation results of Test Case 2 considering Eq. (1) as fitness function

Parameters	Methods				
	Ref.[4]	Ref. [7]	Ref. [11]	Ref. [19]	Proposed ODE
P_{g1} (MW)	11.52	11.17	11.79	11.14	12.23
P_{g2} (MW)	30.55	30.14	30.53	30.11	30.87
P_{g3} (MW)	59.72	52.93	62.48	52.18	55.28
P_{g4} (MW)	98.09	101.95	95.87	100.02	94.72
P_{g5} (MW)	51.42	52.93	50.15	52.81	51.48
P_{g6} (MW)	35.42	36.17	35.03	38.13	35.14
Loss (MW)	3.72	2.29	2.85	1.39	3.28
Fuel Cost ($/hr)	607.78	604.39	606.26	602.55	601.23
Emission	21.99	22.22	21.85	22.20	22.82

Table 6. Simulation results of Test Case 2 considering Eq. (2) as fitness function

Parameters	Methods				
	Ref.[4]	Ref. [7]	Ref. [11]	Ref. [19]	Proposed ODE
P_{g1} (MW)	41.01	40.93	40.88	40.02	49.12
P_{g2} (MW)	46.31	46.25	46.17	44.34	47.82
P_{g3} (MW)	54.35	54.12	54.16	54.25	74.87
P_{g4} (MW)	38.95	38.71	38.73	40.09	80.48
P_{g5} (MW)	54.39	53.91	54.18	55.47	22.37
P_{g6} (MW)	51.50	51.38	51.33	52.68	11.45
Loss (MW)	3.51	2.3	2.45	3.85	1.73
Fuel Cost ($/hr)	645.22	642.68	642.92	643.05	637.61
Emission	19.42	19.41	19.41	20.00	19.39

reduction and combined optimization independently. The total fuel cost, emission and transmission lossunder different circumstances received through ODE. The prize penalty factor for all the 6 generating units are calculated as shown in Table 4. The obtained results have been compared with the results in the literature and tabulated in Table 5, 6 and Table 7. From the table results, it is confirmed that the proposed method outperforms the other methods and produced much more optimum result under all the circumstances. The convergence characteristics of the different methods for the Test Case 2 have been shown through the Fig. 4.

The dynamic capability of the proposed algorithm has been further validated by applying it to 24 hours daily load pattern as shown in Fig. 3. The generating units fuel cost, emission and transmission loss at different timings is shown through the Table 8.

Table 7. Simulation results of Test Case 2 considering Eq. (8) as fitness function

Parameters	Methods				
	Ref.[4]	Ref. [7]	Ref. [11]	Ref. [19]	Proposed ODE
P_{g1} (MW)	27.52	26.95	26.25	33.56	32.45
P_{g2} (MW)	37.52	38.12	37.70	32.32	20.57
P_{g3} (MW)	57.96	54.47	57.60	57.13	66.50
P_{g4} (MW)	67.70	67.90	67.35	66.37	109.12
P_{g5} (MW)	52.83	54.47	53.77	57.85	43.39
P_{g6} (MW)	42.82	43.83	42.70	39.5	14.34
Loss (MW)	3.35	2.74	2.37	3.73	2.66
Fuel Cost ($/hr)	617.57	616.12	615.22	611.45	610.22
Emission	20.00	20.00	20.02	20.08	20.00

Table 8. Simulation results of Test Case 2 at 24 hour load span

Hr	Load (MW)	P_{g1}	P_{g2}	P_{g3}	P_{g4}	P_{g5}	P_{g6}	Loss	Fuel cost ($/hr)	Emis-sion
1	269	11.21	26.08	60.24	38.31	95.21	43.16	3.31	607.89	24.54
2	255	47.05	09.12	65.34	56.86	20.27	60.46	3.32	585.33	21.39
8	226	13.72	21.00	100.27	14.12	19.63	58.08	1.36	538.82	21.86
4	212	22.07	48.47	28.37	11.07	94.11	10.34	1.89	525.21	25.19
5	198	35.86	6.92	50.27	5.0	83.75	16.54	0.36	487.69	24.44
6	277	10.23	5.11	87.17	103.05	46.75	28.04	2.74	605.06	23.34
7	269	11.21	26.08	60.24	38.31	95.21	43.16	3.31	607.89	24.54
8	263	50.00	45.20	59.21	41.93	28.78	41.03	2.71	602.83	21.75
9	283	32.45	20.57	66.50	109.12	43.39	14.34	2.66	610.22	20.00
10	311	23.31	06.22	91.06	120.00	68.29	5.10	2.28	693.37	24.75
11	241	8.00	5.11	75.51	114.27	36.22	5.51	2.23	532.13	23.43
12	255	47.05	09.12	65.34	56.86	20.27	60.46	3.32	585.33	21.39
13	226	13.72	21.00	100.27	14.12	19.63	58.08	1.36	538.82	21.86
14	269	11.21	26.08	60.24	38.31	95.21	43.16	3.31	607.89	24.54
15	277	10.23	5.11	87.17	103.05	46.75	28.04	2.74	605.06	23.34
16	226	13.72	21.00	100.27	14.12	19.63	58.08	1.36	538.82	21.86
17	255	47.05	09.12	65.34	56.86	20.27	60.46	3.32	585.33	21.39
18	212	22.07	48.47	28.37	11.07	94.11	10.34	1.89	525.21	25.19
19	340	21.15	59.97	100.21	109.92	11.32	42.27	4.00	766.35	21.62
20	311	23.31	06.22	91.06	120.00	68.29	5.10	2.28	693.37	24.75
21	283	32.45	20.57	66.50	109.12	43.39	14.34	2.66	610.22	20.00
22	255	47.05	09.12	65.34	56.86	20.27	60.46	3.32	585.33	21.39
23	198	35.86	6.92	50.27	5.0	83.75	16.54	0.36	487.69	24.44
24	198	35.86	6.92	50.27	5.0	83.75	16.54	0.36	487.69	24.44

5.3 Test case 3

The third test case considered for implementation is the system with 13 generating units with a base load of 1800 MW. The fuel cost co-efficient, emission co-efficient and B-loss co-efficient of the test case are detailed in [11, 14] and [15]. The population size and iteration are set as 30 and 100 respectively. The proposed ODE tunes for the optimum with setting the Eq. (1), Eq. (2) and Eq. (8) as the fitness function with considering fuel cost reduction, emission reduction and combined optimization independently. The prize penalty factor for all the 6 generating units are calculated as shown in Table 9. The total fuel cost, emission

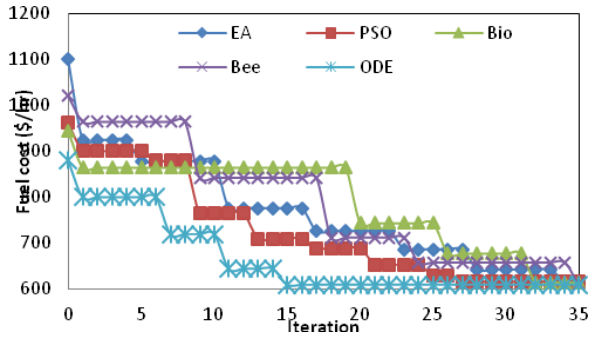


Fig. 4 Convergence characteristic of optimization methods for Test Case 2

Table 9. Prize Penalty factor of generating units of Test Case 3

Gen. Unit	P_{g1}	P_{g2}	P_{g3}	P_{g4}	P_{g5}	P_{g6}	P_{g7}	P_{g8}	P_{g9}	P_{g10}	P_{g11}	P_{g12}	P_{g13}
PPF	1.76	7.58	7.53	7.91	7.91	7.91	7.91	7.9	7.9	1.43	1.43	1.4	1.4

Table 10. Simulation results of Test Case 3

Parameters	Methods					
	Ref. [5]	Ref.[11]	Ref. [17]	Proposed ODE		
				Eq. (1) as fitness function	Eq. (2) as fitness function	Eq. (8) as fitnes s function
P_{g1} (MW)	80.69	179.51	540.52	269.12	277.31	271.91
P_{g2} (MW)	166.30	299.19	225.07	135.41	360.22	360.89
P_{g3} (MW)	166.87	297.57	207.96	363.23	360.87	288.28
P_{g4} (MW)	154.77	159.73	69.09	142.44	111.29	186.26
P_{g5} (MW)	155.41	159.73	84.96	111.04	60.96	155.64
P_{g6} (MW)	154.86	159.73	94.76	60.11	119.71	60.23
P_{g7} (MW)	154.72	159.73	106.97	60.25	110.44	61.54
P_{g8} (MW)	154.52	60.00	109.00	154.18	61.65	60.57
P_{g9} (MW)	154.76	60.00	108.32	159.47	60.62	60.38
P_{g10} (MW)	119.43	40.00	79.63	123.13	40.33	120.45
P_{g11} (MW)	119.29	114.76	63.76	76.16	48.28	46.29
P_{g12} (MW)	109.20	55.00	58.06	69.94	120.13	96.84
P_{g13} (MW)	109.12	55.00	72.96	94.02	92.04	55.56
Loss (MW)	-	-	21.09	18.47	17.92	18.14
Fuel Cost ($/hr)	18,104.04	18,081.48	17,944.84	18,069.54	18,486.70	18,072.24
Emission	-	95.30	-	87.32	74.11	84.33

Table 11. Simulation results of Test Case 3 at 24 hour load span

	Hrs.	5, 23 & 24	4 & 18	3, 13 & 16	11	2, 12, 17 & 22	8	1, 7 & 14	6 & 15	9 & 21	10 & 20	19
	Load (MW)	1260	1350	1440	1530	1620	1680	1710	1765	1800	1980	2160
Generating Units	P_{g1} (MW)	89.21	321.56	399.23	275.71	355.03	401.22	225.24	358.21	271.91	280.11	444.78
	P_{g2} (MW)	342.54	57.23	58.61	20.18	304.48	39.45	360.38	296.74	360.89	213.70	360.32
	P_{g3} (MW)	20.97	45.26	145.22	40.74	35.12	308.22	221.12	328.36	288.28	359.32	309.15
	P_{g4} (MW)	64.23	65.21	60.64	60.29	159.87	60.71	110.31	98.84	186.26	161.82	158.84
	P_{g5} (MW)	70.38	67.89	137.31	166.34	151.55	103.06	162.47	66.65	155.64	60.83	96.19
	P_{g6} (MW)	69.91	157.28	180.04	166.27	62.80	99.87	100.87	73.41	60.23	143.64	180.37
	P_{g7} (MW)	111.29	60.47	105.69	163.20	60.11	124.82	60.33	60.32	61.54	110.35	112.68
	P_{g8} (MW)	180.58	180.68	60.20	136.09	60.97	180.74	163.85	108.98	60.57	162.29	107.64
	P_{g9} (MW)	121.55	159.93	112.91	111.28	174.61	60.31	60.54	60.79	60.38	158.10	60.47
	P_{g10} (MW)	42.32	39.26	40.39	113.48	53.41	80.96	89.84	40.49	120.45	104.33	40.55
	P_{g11} (MW)	44.72	45.26	43.82	120.64	82.22	78.36	49.12	113.56	46.29	120.20	116.64
	P_{g12} (MW)	57.23	109.22	55.18	115.24	55.70	93.74	56.02	93.23	96.84	55.06	79.97
	P_{g13} (MW)	57.23	55.45	55.18	55.67	70.77	65.72	55.87	72.77	55.56	55.06	99.21
	Loss (MW)	12.16	14.64	14.42	15.18	16.74	17.85	17.45	18.08	18.14	19.17	20.71
	Fuel Cost ($/hr)	14143.52	14863.49	15492.48	16485.30	17224.01	17660.60	18009.21	18,024.65	18,072.24	20,193.38	21,732.32
	Emission	84.28	85.56	87.08	83.35	84.77	86.75	83.15	84.95	84.33	82.68	90.62

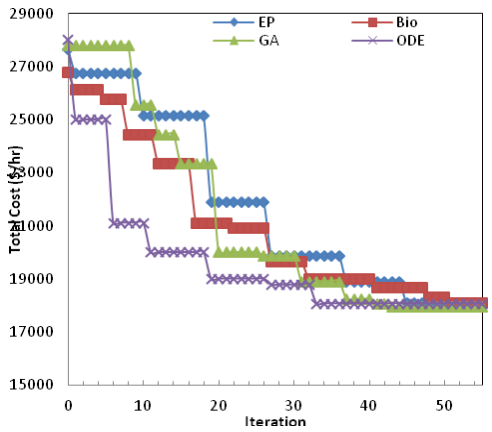


Fig. 5. Convergence characteristic of optimization methods for test case 3

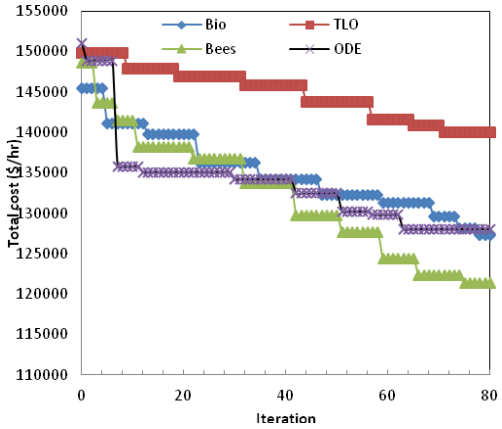


Fig. 6. Convergence characteristic of optimization methods for Test Case 4

and transmission loss under different circumstances received through ODE. The obtained results have been compared with the results in the literature and tabulated in Table 10. From the table results, it is confirmed that the proposed method outperforms the other methods and produced much more optimum result under all the circumstances. The convergence characteristics of the different methods for the Test Case 3 have been shown through the Fig. 5.

The dynamic capability of the proposed algorithm has been further validated by applying it to 24 hours daily load pattern with Eq. (8) as fitness function. The generating units cost and total cost at different timings is shown through the Table 11. The Table evident that the proposed ODE algorithm has produced the optimum results under different loadings.

5.4 Test case 4

The next test case considered for implementation is the system with 40 generating units with a base load of 10500 MW. The fuel cost co-efficient and emission co-efficient with valve point effect of the test case are detailed in [11], [14] and [15]. The population size and iteration are set as 100 and 120 respectively. With the effective implementation of the proposed ODE, the fuel cost and emission are simultaneously optimized by keeping the Eq. (8) as the fitness function. The obtained results have been compared with the results in the literature and tabulated in Table 12. From the table results, it is confirmed that the proposed method outperforms the other methods and produced much more optimum result under all the circumstances. The convergence characteristics of the different methods for the Test Case 4 have been shown through the Fig. 6.

The dynamic capability of the proposed algorithm has been further validated by applying it to 24 hours daily load pattern with Eq. (8) as fitness function. The generating units cost and total cost at different timings is shown through the Table 13. The Table evident that the proposed ODE algorithm has produced the optimum results under different loadings. Thus, from the Figures Fig. 3, 4, 5 and Fig. 6, it is clear that the convergence in obtaining

Table 12. Simulation results of Test Case 4

Parameters	Methods			
	Ref. [11]	Ref.[15]	Ref. [18]	Proposed ODE
P_{g1} (MW)	114.00	114.00	110.79	96.43
P_{g2} (MW)	114.00	114.00	110.79	114.11
P_{g3} (MW)	120.00	120.00	97.40	81.41
P_{g4} (MW)	179.73	181.35	179.73	188.23
P_{g5} (MW)	97.00	97.00	97.80	97.98
P_{g6} (MW)	132.97	106.07	140.00	140.58
P_{g7} (MW)	300.00	300.00	259.59	300.00
P_{g8} (MW)	292.05	298.10	284.59	276.06
P_{g9} (MW)	291.64	294.16	284.60	300.26
P_{g10} (MW)	279.59	275.52	130.00	130.25
P_{g11} (MW)	312.55	314.15	94.00	375.01
P_{g12} (MW)	311.60	308.19	94.00	294.35
P_{g13} (MW)	394.52	484.99	214.76	247.18
P_{g14} (MW)	395.59	472.69	394.28	348.25
P_{g15} (MW)	394.85	476.33	394.28	500.34
P_{g16} (MW)	395.36	480.71	394.27	513.85
P_{g17} (MW)	456.69	480.90	489.27	489.00
P_{g18} (MW)	464.11	482.18	489.27	532.00
P_{g19} (MW)	421.58	502.80	511.27	496.98
P_{g20} (MW)	421.67	506.34	511.27	508.32
P_{g21} (MW)	433.52	514.72	523.28	550.22
P_{g22} (MW)	433.52	515.85	523.28	550.87
P_{g23} (MW)	433.53	483.04	523.28	546.94
P_{g24} (MW)	433.53	431.11	523.28	534.99
P_{g25} (MW)	433.51	509.03	523.27	515.22
P_{g26} (MW)	433.52	508.60	523.28	550.77
P_{g27} (MW)	17.18	18.45	10.00	10.31
P_{g28} (MW)	20.44	21.50	10.00	10.62
P_{g29} (MW)	22.72	10.01	10.00	22.00
P_{g30} (MW)	97.00	87.72	87.80	95.97
P_{g31} (MW)	168.53	190.00	190.00	249.39
P_{g32} (MW)	170.11	190.00	190.00	177.37
P_{g33} (MW)	170.98	190.00	190.00	195.26
P_{g34} (MW)	200.00	200.00	164.79	200.00
P_{g35} (MW)	200.00	200.00	200.00	200.84
P_{g36} (MW)	200.00	200.00	194.40	190.30
P_{g37} (MW)	106.77	110.00	109.99	94.06
P_{g38} (MW)	107.11	110.00	109.99	172.08
P_{g39} (MW)	106.84	110.00	109.99	189.99
P_{g40} (MW)	421.55	506.80	511.28	368.74
Loss (MW)	Not considered	1016.45	Not considered	981.23
Fuel cost($/hr)	127335.40	139962.99	121412.75	128063.71
Emission	97848.41	381772.96	359901.95	387601.79

the optimum solution through ODE is much better than the other optimization techniques used for this purpose, irrespective of nature of the system.

The main contributions of the proposed work are,

i. Development and implementation of self tuned ODE for the optimal dispatch
ii. Algorithm specific control parameters were fine tuned automatically
iii. ODE has a special property of generation jumping which provides much faster convergence to the solution
iv. Consideration of fuel cost and emission simultaneously
v. Suitability of the algorithm under different systems under different loading conditions

6. Conclusion

An efficient approach with the unique features such asgeneration jumping, self acceleration, self migration, self tuning of the algorithm specific control parameters and assured optimal search with least population size and iteration, to solve Economic Emission Load Dispatch (EELD) has been revealed through implementing the algorithm into three standard test cases. The research work has been carried out with setting different fitness functions according to the objectives such as minimization of fuel cost, minimization of emission and combination of both. The proposed ODE tunes for the optimum with considering fuel cost reduction, emission reduction and combined optimization independently. Furthermore, the robustness of the proposed algorithm has been verified by applying the test cases to 24hr daily load span, the proposed ODE algorithm has produced best compromise solution between fuel cost and emission along with the operating constraints. Moreover, the proposed ODE algorithm does not require any sort of assumptions and/or trial and error practices for setting up the control parameters. Finally, the results were compared with the results in the literature, the results evident that the proposed algorithm outperforms the other algorithms in EELD.

Nomenclature

a_{gi}, b_{gi} and c_{gi}	fuel cost coefficients of the gi^{th} generator
$F_{g,cost}$	Fuel cost of the generators
Ng	Total number of generators
$F_{g,emission}$	Emission cost of the generators
P_{gi}	Real power generated at the gi^{th} generator
P_{Demand}	Load demand of the system
$P_{tr,loss}$	Transmission loss of the system
B_{ij}	Loss co-efficients of the system
$P_{gi,min}$, $P_{gi,max}$	Minimum and Maximum generation of the gi-th generator of the system
D_{gi}, U_{gi}	Upper and Lower values of the difference
F_{eeld}	Economic Emission Load Dispatch
PPF_{gi}	Prize Penalty Factor of the gi-th generator of the system

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Table 13 Simulation results of Test Case 4 at 24 hour load span

Hrs.		5, 23 & 24	4 & 18	3, 13 & 16	11	2, 12, 17 & 22	8	1, 7 & 14	6 & 15	9 & 21	10 & 20	19
Load (MW)		7350	7875	8400	8925	9450	9765	9975	10290	10500	11550	12600
Generating Units	P_{g1} (MW)	36.37	36.02	86.03	60.82	70.47	36.97	84.89	70.55	96.43	114.52	114.32
	P_{g2} (MW)	73.11	46.78	114.83	107.57	112.68	114.00	114.64	114.25	114.11	114.90	114.34
	P_{g3} (MW)	93.12	100.00	69.22	120.99	120.86	60.50	60.78	87.09	81.41	120.57	120.14
	P_{g4} (MW)	80.24	190.74	130.32	80.26	125.50	131.40	188.82	168.57	188.23	189.18	190.74
	P_{g5} (MW)	97.99	47.00	89.84	62.33	72.06	90.56	81.50	53.67	97.98	97.78	97.23
	P_{g6} (MW)	106.00	113.00	101.43	94.31	138.21	140.53	129.61	127.59	140.58	139.63	140.25
	P_{g7} (MW)	104.00	128.98	300.12	100.91	300.10	104.69	181.10	272.96	300.00	300.69	300.31
	P_{g8} (MW)	135.00	192.00	169.35	212.87	273.00	232.02	213.09	300.43	276.06	297.40	300.00
	P_{g9} (MW)	225.44	246.19	300.34	241.65	275.13	293.02	240.02	273.54	300.26	300.84	300.25
	P_{g10} (MW)	130.28	136.21	203.80	136.62	138.71	240.68	300.01	130.55	130.25	298.24	300.69
	P_{g11} (MW)	100.00	242.30	94.94	94.94	94.89	370.04	94.43	94.62	375.01	367.04	375.53
	P_{g12} (MW)	208.51	195.00	193.06	94.36	243.50	94.93	94.45	205.27	294.35	373.63	375.58
	P_{g13} (MW)	419.00	482.00	195.20	125.64	452.09	125.24	125.43	464.91	247.18	497.77	500.35
	P_{g14} (MW)	356.38	125.00	221.50	379.53	477.72	308.13	430.07	488.99	348.25	496.38	500.66
	P_{g15} (MW)	417.00	143.00	232.35	125.99	441.03	125.34	500.70	425.72	500.34	500.21	500.22
	P_{g16} (MW)	394.00	129.66	343.73	500.91	218.25	239.79	424.06	233.77	513.85	437.32	500.47
	P_{g17} (MW)	325.78	550.93	550.31	550.40	434.45	377.55	482.74	508.68	489.00	546.94	550.20
	P_{g18} (MW)	220.00	282.00	258.80	550.99	507.54	433.21	499.99	486.43	532.00	526.13	550.52
	P_{g19} (MW)	509.00	352.11	242.16	500.83	323.74	427.63	489.14	347.52	496.98	550.04	550.22
	P_{g20} (MW)	338.89	550.00	242.83	337.23	415.58	518.70	242.13	469.41	508.32	548.89	550.63
	P_{g21} (MW)	313.00	550.00	529.31	364.08	391.52	550.33	550.45	550.67	550.22	522.26	550.42
	P_{g22} (MW)	349.00	320.00	475.36	352.79	514.08	550.01	477.43	374.84	550.87	550.84	550.52
	P_{g23} (MW)	319.10	254.76	550.70	550.06	517.04	463.92	478.00	550.24	546.94	550.99	550.02
	P_{g24} (MW)	254.00	319.00	550.52	539.60	254.46	550.79	544.27	550.90	534.99	550.54	550.19
	P_{g25} (MW)	261.81	254.45	494.84	550.06	515.09	536.44	550.22	548.84	515.22	550.07	550.54
	P_{g26} (MW)	492.00	386.00	254.31	518.71	459.24	550.16	384.62	550.42	550.77	550.92	550.53
	P_{g27} (MW)	47.00	97.00	29.02	21.43	57.48	100.82	127.37	90.85	10.31	150.84	150.11
	P_{g28} (MW)	40.00	56.61	150.46	85.18	60.23	85.37	10.25	140.94	10.62	150.67	150.11
	P_{g29} (MW)	114.79	10.37	10.39	40.71	10.77	37.01	24.48	14.06	22.00	72.58	150.64
	P_{g30} (MW)	59.37	47.00	48.36	54.98	49.80	97.37	97.68	97.34	95.97	97.57	97.19
	P_{g31} (MW)	60.46	60.41	168.33	71.15	142.05	190.99	159.40	80.59	249.39	190.61	190.12
	P_{g32} (MW)	129.00	142.00	132.52	147.78	150.43	145.06	190.59	190.24	177.37	190.74	190.06
	P_{g33} (MW)	125.94	137.00	190.89	65.89	60.93	154.37	136.53	60.68	195.26	175.31	190.46
	P_{g34} (MW)	173.00	98.00	161.35	98.88	123.28	105.64	179.61	150.80	200.00	198.84	200.85
	P_{g35} (MW)	137.00	200.00	200.18	200.82	128.43	178.55	97.68	90.42	200.84	200.13	200.44
	P_{g36} (MW)	90.00	200.00	90.82	200.25	158.32	163.52	147.24	195.65	190.30	198.75	200.81
	P_{g37} (MW)	31.75	110.83	110.44	110.44	39.00	110.23	108.85	99.74	94.06	110.53	110.08
	P_{g38} (MW)	63.00	25.00	30.12	27.18	44.99	97.20	79.98	60.33	172.08	110.63	110.74
	P_{g39} (MW)	94.88	84.00	110.01	98.79	25.11	84.35	110.05	25.48	189.99	110.18	110.20
	P_{g40} (MW)	242.00	242.00	489.81	370.25	519.25	550.01	546.30	550.37	368.74	550.06	550.10
	Loss (MW)	410.76	446.12	519.27	602.06	683.93	724.61	799.33	876.40	981.23	1045.84	1121.23
Fuel Cost ($/hr)		105944.54	98026.28	104543.67	110105.01	116961.93	117770.56	121915.65	126172.09	128063.71	156999.16	168510.28
Emission		56070.15	132070.17	74482.57	294807.48	168532.43	354438.43	290063.54	363135.29	387601.79	611250.89	679858.55