

# Deterministically guided differential evolution for constrained power dispatch with prohibited operating zones

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**Abstract:** This paper presents a new approach to solve economic load dispatch (ELD) problem in thermal units with non-convex cost functions using differential evolution technique (DE). In practical ELD problem, the fuel cost function is highly non linear due to inclusion of real time constraints such as valve point loading, prohibited operating zones and network transmission losses. This makes the traditional methods fail in finding the optimum solution. The DE algorithm is an evolutionary algorithm with less stochastic approach to problem solving than classical evolutionary algorithms. DE have the potential of simple in structure, fast convergence property and quality of solution. This paper presents a combination of DE and variable neighborhood search (VNS) to improve the quality of solution and convergence speed. Differential evolution (DE) is first introduced to find the locality of the solution, and then VNS is applied to tune the solution. To validate the DE-VNS method, it is applied to four test systems with non-smooth cost functions. The effectiveness of the DE-VNS over other techniques is shown in general.

**Key words:** economic load dispatch, differential evolution, variable neighborhood search, prohibited operating zones, valve point effect

## 1. Introduction

Economic Load Dispatch (ELD) problem is an important optimization task in power system operation [4]. The main objective of ELD problem is the allocation of power generation to different generating units so as to minimize the operating cost while satisfying various physical constraints. This makes the ELD problem a large-scale non-linear constrained optimization problem [1, 2]. Earlier, conventional methods such as lagrangian relaxation (LR), linear programming (LP), non-linear programming (NLP), dynamic programming (DP) and few gradient based methods are used to solve the ELD problem. However all of these methods may not be able to find an optimal solution and usually stuck at a local optimum solution. Other disadvantage includes approximation of cost function, solution accuracy, dependency on initial reach point.

These problems can be overcome by using heuristic techniques such as Evolutionary Programming (EP) [5], Genetic Algorithm (GA) [4], Simulated Annealing (SA) [13], Neural Network (NN) [6], Particle Swarm Optimization (PSO) [7] and Differential Evolution [14].

In the recent past, as an alternative to the heuristic approaches, several hybrid optimization methods such as particle swarm optimization with local search (PSO-LS) [17], multi-objective differential evolution (MODE) [18], improved particle swarm optimization (IPSO) [19], adaptive hybrid differential evolution (AHDE) [20], chaotic sequence based differential evolution (CSDE) [21], hybrid interior point assisted differential evolution (IP\_DE) [22] and differential evolution with biogeography based optimization (DE\_BBO) [23] have been introduced to solve ELD problem with non-convex objective functions.

Differential Evolution developed by Storn and Price is one of the excellent evolutionary algorithms. DE is a robust statistical method for cost function minimization, which does not make use of a single parameter vector but instead uses a population of equally important vectors. Differential Evolution (DE) is one of the most recent population-based techniques. The DE algorithm has been applied to various fields of power system optimization. DE is an extremely powerful yet simple evolutionary algorithm that improves a population of individuals over several generations through the operators of mutation, crossover and selection. Differential evolution presents great convergence characteristics and requires few control parameters [14, 15] which remain fixed throughout the optimization process and need minimum tuning. Though DE seems to be good method to solve non-smooth economic load dispatch (NSELDP) problem, it suffers from the problem of choosing the control parameters. Therefore hybrid methods of combining two or more methods are introduced. Hybrid methods combining probabilistic method and deterministic method are found to be more effective in solving NSELDP problem [3, 8].

The purpose of this paper is to present a solution methodology combining differential evolution and variable neighborhood search technique (DE-VNS). The hybrid method is applied for four different test systems including valve point effect, ramp rate limits and prohibited operating zones.

## 2. Problem formulation

### 2.1. Objective function

The cost function of generating units and the major component of the operating costs for thermal units are generally given in a quadratic polynomial as it is shown in Equation (1)

$$\text{Minimize } F_T = \left( \sum_{i=1}^N F_i(P_i) \right) (\$). \quad (1)$$

The fuel cost function of the  $i$ th generating unit is represented as follows:

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i + \left| e_i \times \sin \left\{ f_i \times (P_i^{\min} - P_i) \right\} \right| (\$/\text{hr}), \quad (2)$$

where  $N$  is the total number of generating units.  $a_i$ ,  $b_i$  and  $c_i$  are fuel-cost coefficients of the  $i$ th generating unit.  $e_i$  and  $f_i$  are constants from the valve point effect of the  $i$ th generating unit.  $P_i$  is the power output of the  $i$ th generating unit in megawatts and  $F_T$  is the total fuel cost of all the generating units. The objective function is subject to:

## 2.2. Real power balance

$$\sum_{i=1}^N P_i - P_D - P_L = 0, \quad (3)$$

where  $P_D$  is the power demand in megawatts.  $P_L$  is the power loss in megawatts and it is calculated as follows:

$$P_L = \sum_{i=1}^m \sum_{j=1}^m P_i B_{ij} P_j + \sum_{i=1}^m B_{0i} P_i + B_{00}. \quad (4)$$

## 2.3. Real power generation limit

$$P_{i\min} \leq P_i \leq P_{i\max}, \quad (5)$$

where  $P_{i\min}$  is the minimum limit and  $P_{i\max}$  is the maximum limit of the real power of the  $i$ th generating unit in megawatts.

## 2.4. Ramp rate limits

The actual operating range of all online units is restricted by their corresponding ramp rate limits. Therefore Equation (5) is modified as follows:

$$\max(P_{i\min}, P_{i0} - DR_i) \leq P_i \leq \min(P_{i\max}, P_{i0} + UR_i). \quad (6)$$

Where  $P_{i0}$  is the previous power output of the  $i$ th generating unit,  $UR_i$  and  $DR_i$  are the up and down ramp limits of the  $i$ th generating in megawatts respectively.

## 2.5. Prohibited operating zones

The feasible operating zones of a unit can be described as follows:

$$P_i \in \begin{cases} P_{i,\min} \leq P_i \leq P_{i,1}^l \\ P_{i,k-1}^u \leq P_i \leq P_{i,k}^l, & k = 2, 3, \dots, pz_i \\ P_{i,pz_i}^u \leq P_i \leq P_{i,\max}, & i = 1, 2, \dots, n_{pz}, \end{cases} \quad (7)$$

where  $P_{i,k}^l / P_{i,k}^u$  are the lower and upper bounds of the prohibited operating zone of  $i$ th generating unit,  $pz_i$  is the number of prohibited operating zones of the  $i$ th generating unit and  $n_{pz}$  is the number of units having prohibited operating zones.

### 3. Differential evolution

Differential evolution (DE) was designed as a stochastic direct search method to handle non-differentiable, nonlinear and multimodal cost functions. DE starts with an initial population  $NP$  that is generated by adding normally distributed random deviations to the nominal solution. The initial population utilizes  $NP$   $D$ -dimensional parameter vectors for each generation, whereas  $D$  represents dimension of the problem. The  $i$ th individual in the population is represented by following expression:

$$\vec{X}_i = [x_{1i}, x_{2i}, x_{3i}, \dots, x_{Di}]. \quad (8)$$

The initial population should better cover the entire search space as much as possible by uniformly randomizing individuals within the search space constrained by the prescribed minimum and maximum parameter bounds. The  $i$ th individual of the population for current generation  $G$  is given by following expression:

$$x_{ij,G} = x_{ij}^{\min} + \text{rand}(0, 1) \cdot (x_{ij}^{\max} - x_{ij}^{\min}), \quad (9)$$

where  $j = 1, 2, \dots, D$  and  $\text{rand}(0, 1)$  represents a uniformly distributed random variable within the range  $[0, 1]$   $x_{ij}^{\max}$  and  $x_{ij}^{\min}$  represents higher and lower bounds of the search space. The initial population is subjected to following different operations.

#### 3.1. Mutation

For each target vector  $X_{i,G}$ , a mutant vector is generated as follows:

$$V_{i,G+1} = x_{r1,G} + F(x_{r2,G} - x_{r3,G}), \quad (10)$$

where random indexes,  $r1, r2, r3 \in \{1, 2, \dots, NP\}$  are integers that is mutually different to each other and to the running index  $i$ .  $F$  is a real and constant factor which controls the amplification of different variation  $(x_{r2,G} - x_{r3,G})$ . It is the method of creating this donor vector that differentiates one DE scheme from another. The Equation (10) is known as “DE/rand/1” strategy and throughout this paper the strategy “DE/rand/1” is followed.

#### 3.2. Crossover

To increase the diversity of the perturbed vectors, crossover is introduced. It results in formation of a trial vector which is represented as:

$$u_{i,G+1} = (u_{1i,G+1}, u_{2i,G+1}, u_{3i,G+1}, \dots, u_{Di,G+1}). \quad (11)$$

The crossover is applied to each pair of target vector,  $X_{i,G}$  and mutant vector,  $V_{i,G}$  to form a trial vector. It is performed by following expression:

$$u_{ji,G+1} = \begin{cases} v_{ji,G+1} & \text{if } (\text{rand } b(j) \leq CR) \\ x_{ji,G} & \text{if } (\text{rand } b(j) > CR), \text{ where } j = 1, 2, \dots, D, \end{cases} \quad (12)$$

where  $j = 1, 2, \dots, D$  and  $\text{rand } b(j)$  is the  $j$ th evaluation of a uniform random number generator with outcome  $\varepsilon \in [0, 1]$ .  $CR$  is the crossover constant  $\varepsilon \in [0, 1]$ .

### 3.3. Selection

To decide whether or not  $U_{i,G+1}$  should become a member of generation  $G + 1$ , it is compared to the target vector  $X_{i,G}$  using the greedy criterion. It is given as follows:

$$x_{i,G+1} = \begin{cases} u_{i,G+1} & \text{if } f(u_{i,G+1}) < f(x_{i,G}) \\ x_{i,G} & \text{otherwise.} \end{cases} \quad (13)$$

Set the generation number for  $G = G + 1$ . Repeat the above steps until a stopping criterion is met, usually a maximum number of iterations (generations),  $G_{\max}$ .

## 4. Variable neighborhood search

Variable neighborhood search (VNS) is a metaheuristic which relies on iteratively exploring neighbourhoods of mounting amount to classify improved limited optima [10]. VNS follow a methodical alter of neighborhood surrounded by a local search. The policy for the VNS involve iterative examination of better neighborhoods for a given local optima awaiting an upgrading is to be found after which time the hunt across expanding neighborhoods is continual. VNS involves the following steps,

Replicate the subsequent steps until the stopping state is met:

- 1) Set  $k \leftarrow 1$ .
- 2) Until  $K = K_{\max}$ , repeat the following steps:
  - (a) generate a point  $x'$  at random from the  $k^{\text{th}}$  neighborhood of  $x (x' \in N_k(x))$ ,
  - (b) apply some local search method with  $x'$  as initial solution; denote with  $x''$  the so obtained local optimum,
  - (c) if  $f(x'') < f(x')$  then

$$(x \leftarrow x''),$$

$$(k \leftarrow k + 1).$$

Otherwise, set  $k \leftarrow k + 1$ .

## 5. Implementation of DE-VNS for NSELD problem

### Step 1. Parameter setup

Initialize the number of generating units  $N$  and Population size  $NP$ . Specify minimum and maximum capacity of each generator  $P_{imin}$  and  $P_{imax}$  respectively. Initialize DE parameters like Crossover Probability  $CR$ , Scaling Factor  $F$ . Set generation count,  $G = 0$ .

### Step 2. Initialization of the population

For a population size NP and dimension D, an initial vector  $X_{ij,G}$  is randomly generated. D represents the number of decision variables to be optimized. In ELD problem D is the number of generating units considered.  $X_{ij}$  is the real power value of  $j$ th unit of the  $i$ th population randomly generated within the operating limits using Equation (9).

### Step 3. Evaluation of fitness function

Evaluate the fitness value of each individual vector  $X_{ij}$ . The evaluation function  $f(P_i)$  is defined to minimize the fuel cost function given by (1) for a given load demand  $P_D$  while satisfying the constraints given by Equations (3), (5), (6) and (7).

$$f(P_i) = \sum_{i=1}^N F_i(P_i) + \lambda \cdot \left[ \sum_{i=1}^N P_i - P_D \right]^2 + \gamma \cdot \left[ \sum_{i=1}^n v_i^R \right], \quad (14)$$

where  $\lambda$  is the penalty parameter for not satisfying the load demand and  $\gamma$  represents the penalty for a unit loading falling within a prohibited operating zone  $v_i^R$  is the violation of the prohibited zone constraint for the  $i$ th unit which is defined as

$$v_i^R = \begin{cases} 1 & \text{if } P_i \text{ violates the prohibited zones} \\ 0 & \end{cases} \quad (15)$$

### Step 4. Mutation operation

For each target vector  $X_{i,G}$ , a mutant vector  $V_{i,G}$  is generated for the strategy DE/rand/1 using Equation (12).

### Step 5. Recombination

Recombination is employed to generate a trial vector  $U_i$  by replacing certain parameters of  $X_i$  with corresponding parameters of donor vector  $V_i$ . The trial vector by crossover operation is obtained using Equation (12) and its fitness is evaluated using (14).

### Step 6. Selection

Members to constitute the population of next generation ( $G + 1$ ) are decided by (13). The new vector  $X_{i,(G+1)}$  is selection based on the comparison of fitness value of both  $X_i$  and  $U_i$ .

### Step 7. Invoke VNS

After the selection process the VNS procedure is invoked as given in the Section 4.

### Step 8. Verification of stopping criterion

Set the generation count  $G = G + 1$ . Go to step 3 until stopping criterion is met usually maximum generation count  $G_{\max}$ .

## 6. Results and discussion

The efficiency of the hybrid technique is examined with four test systems of 3, 10, 15 and 40 generating unit system. The test cases are simulated for 50 trial runs. To validate superiority and fitness of the proposed method, the DE-VNS is compared with GA, PSO, modified PSO (MPSO), DE/rand/1 (DE(1)) and DE/rand/2 (DE(2)). The software has been printed in MATLAB language and performed on a Pentium Dual private processor with 1400-MB RAM. In this work, the population size  $N = 50$ ,  $F = 0.8$ ,  $CR = 0.6$  and the termination criterion  $G_{\max} = 500$  generations is taken.

### 6.1. Case 1

This test case is a 3-unit system considering the transmission losses, ramp rate limits and prohibited operating zones. This test system consists of 3 units with valve point loading and has a load demand of 850 MW. The input data are given in [11]. The results obtained by the proposed method are compared with other methods. Table 1 shows the comparison with different methods [16]. It is clear from Table 1 that the proposed method produces much better solution compared to other methods. It can also be seen that the average fuel cost produced by DE-VNS is less compared to other methods.

Table 1. Comparison of best scheduling of units for case 1

Power output	PSO	MPSO	DE(1)	DE(2)	DE-VNS
P1 (MW)	202.320	199.599	170.511	156.433	197.983
P2 (MW)	245.514	233.763	384.972	400.000	331.436
P3 (MW)	585.323	598.665	505.268	510.833	515.322
P <sub>L</sub> (MW)	183.814	182.028	210.752	217.266	194.742
P <sub>D</sub> (MW)	850.000	850.000	850.000	850.000	850.000
Total Gen.	1033.157	1032.028	1060.752	1067.266	1044.742
Max. Cost	10123.536	10104.137	10074.251	10046.516	9929.760
Avg. Cost	10100.827	10098.230	10067.987	10041.179	9923.489
Best Cost	10097.575	10097.575	10067.312	10040.504	<b>9922.814</b>

### 6.2. Case 2

This test case is a 10-unit system considering the transmission losses, ramp rate limits and prohibited operating zones. This test system consists of 10 units with valve point loading and has a load demand of 2000 MW. The input data are given in [4]. The results obtained by the proposed method are compared with other methods. Table 2 shows the comparison with different methods [16]. It is clear from Table 2 that the proposed method produces much better solution compared to other methods. It can also be seen that the average fuel cost produced by DE-VNS is less compared to other methods.

Table 2. Comparison of best scheduling of units for case 2

Power output	PSO	MPSO	DE(1)	DE(2)	DE-VNS
P1(MW)	226.624	236.567	189.967	178.647	183.818
P2(MW)	232.781	242.156	201.552	243.387	225.720
P3(MW)	340.000	340.000	340.000	340.000	340.000
P4(MW)	300.000	300.000	300.000	300.000	300.000
P5(MW)	243.000	243.000	243.000	243.000	243.000
P6(MW)	160.000	160.000	160.000	160.000	160.000
P7(MW)	130.000	130.000	130.000	130.000	130.000
P8(MW)	120.000	120.000	120.000	120.000	120.000
P9(MW)	80.000	80.000	80.000	80.000	80.000
P10(MW)	243.948	223.326	313.311	282.606	295.158
P <sub>L</sub> (MW)	76.354	76.543	77.8314	77.6422	77.698
P <sub>D</sub> (MW)	2000.000	2000.000	2000.000	2000.000	2000.000
Total Gen.	2076.354	2076.543	2077.830	2077.640	2077.690
Max. Cost	133397.184	129173.281	128778.480	128579.090	128254.490
Avg. Cost	127449.197	126494.824	126100.023	125900.639	125576.039
Best Cost	126015.507	126015.507	125620.706	125421.322	<b>125096.722</b>

### 6.3 Case 3

This test case is a 15-unit system considering the transmission losses, ramp rate limits and prohibited operating zones. This test system consists of 15 units with valve point loading and has a load demand of 2630MW. The input data are given in [7]. The results obtained by the proposed method are compared with other methods. Table 3 shows the comparison with different methods [7]. It is clear from Table 3 that the proposed method produces much better solution compared to other methods. It can also be seen that the average fuel cost produced by DE-VNS is less compared to other methods.

Table 3. Comparison of best scheduling of units for case 3

Power output	GA	PSO	DE(1)	DE(2)	DE-VNS
P1(MW)	415.310	439.116	455.000	455.000	455.000
P2(MW)	359.720	407.9727	455.000	455.000	455.000
P3(MW)	104.425	119.632	130.000	130.000	130.000
P4(MW)	74.985	129.992	130.000	130.000	130.000
P5(MW)	380.284	151.068	328.167	236.947	236.935
P6(MW)	426.790	459.997	371.534	460.000	460.000
P7(MW)	341.316	425.560	465.000	465.000	465.000
P8(MW)	124.786	98.569	60.000	60.000	60.000
P9(MW)	133.144	113.493	25.000	25.000	25.000



P10(MW)	89.256	101.114	25.000	25.000	25.000
P11(MW)	60.057	33.911	80.000	80.000	80.000
P12(MW)	49.999	79.958	80.000	80.000	80.000
P13(MW)	38.771	25.004	25.000	25.000	25.000
P14(MW)	41.942	41.414	15.000	15.000	15.000
P15(MW)	22.644	35.614	15.000	15.000	15.000
P <sub>L</sub> (MW)	38.278	32.430	29.687	26.935	26.935
P <sub>D</sub> (MW)	2630.000	2630.000	2630.000	2630.000	2630.000
Total gen.	2668.278	2662.430	2659.687	2656.935	2656.935
Max. cost	33337.000	33331.000	32886.000	32862.000	32853.000
Avg. cost	33228.000	33039.000	32634.000	32751.000	32727.000
Best cost	33113.000	32858.000	32606.285	32560.583	<b>32548.249</b>

#### 6.4 Case 4

This test system consists of 40 units with valve point loading and has a load demand of 10500MW. The input data are given in [12]. The results obtained by the proposed method are compared with other methods. Table 4 shows the comparison with different methods. It is clear from Table 4 that the proposed method produces a much better solution compared to other methods [12]. It can also be seen that the average fuel cost produced by DE-VNS is less compared to other methods.

Table 4. Comparison of best scheduling of units for case 4

Power output	GA	DE	HDE	ST- HDE	DE-VNS
P1(MW)	111.721	113.576	113.978	110.846	113.940
P2(MW)	110.611	113.792	114.000	112.156	114.000
P3(MW)	99.160	97.405	98.530	120.000	60.000
P4(MW)	179.796	180.005	182.822	179.465	190.000
P5(MW)	90.213	89.619	91.995	93.171	97.000
P6(MW)	139.740	139.999	139.125	139.655	89.500
P7(MW)	261.078	299.999	299.204	299.990	300.000
P8(MW)	285.748	284.704	285.674	292.931	300.000
P9(MW)	285.455	284.611	296.191	284.574	300.000
P10(MW)	130.000	130.000	200.000	130.000	300.000
P11(MW)	169.322	94.214	94.667	94.009	262.055
P12(MW)	169.860	168.794	169.386	94.000	94.000
P13(MW)	300.000	304.436	125.000	125.000	358.189
P14(MW)	392.837	394.279	394.566	393.650	500.000
P15(MW)	305.453	394.279	484.717	478.767	125.000
P16(MW)	383.771	304.519	304.512	393.102	338.043
P17(MW)	489.595	489.279	491.361	489.110	500.000

P18(MW)	489.140	489.279	489.471	489.073	500.000
P19(MW)	510.408	511.279	511.472	511.215	291.920
P20(MW)	511.415	511.298	511.545	511.046	523.879
P21(MW)	524.101	523.279	524.463	523.186	550.000
P22(MW)	523.680	523.985	526.872	530.590	474.304
P23(MW)	522.611	523.720	524.733	523.146	550.000
P24(MW)	526.853	523.284	523.287	522.994	474.540
P25(MW)	522.965	523.306	524.115	523.673	550.000
P26(MW)	522.985	523.279	523.226	525.244	550.000
P27(MW)	10.625	10.000	10.171	10.000	15.528
P28(MW)	10.584	10.167	10.000	10.027	10.000
P29(MW)	11.369	10.000	10.639	10.000	10.000
P30(MW)	88.390	91.165	91.942	89.012	97.000
P31(MW)	189.986	189.988	190.000	188.854	190.000
P32(MW)	189.040	189.999	187.237	189.998	190.000
P33(MW)	185.847	189.995	190.000	189.613	60.000
P34(MW)	166.836	199.999	165.687	200.000	200.000
P35(MW)	199.790	199.999	200.000	199.999	141.096
P36(MW)	199.976	165.846	174.897	199.917	200.000
P37(MW)	92.016	109.999	110.000	108.443	110.000
P38(MW)	107.194	99.308	109.925	110.000	110.000
P39(MW)	99.503	105.924	109.825	110.000	110.000
P40(MW)	511.309	511.279	512.157	511.268	550.000
Total Gen.	10500.000	10500.000	10500.000	10500.000	10500.000
Max. Cost	124668.690	129639.790	124855.800	124570.740	123407.873
Avg. Cost	124076.430	127399.360	124210.340	124007.100	122084.000
Best Cost	123652.240	125074.400	123598.760	123496.020	<b>122333.153</b>

## 7. Conclusion

A hybrid approach by fine tuning DE with VNS for solving the NSELD problem of units with valve-point effects is presented. An optimal range of mutation rate, neighborhood size, and crossover rate for the VNS tuned DE algorithm is estimated to solve all the test cases considered in this paper. The feasibility of the method was illustrated by conducting case studies with valve-point effects and ramp rate limits and compared with the results obtained by the other methods. The fuel cost obtained by all the test cases shows the superiority of the proposed hybrid VNS guided DE method over other optimization techniques for NSELD problem.

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