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# An Improved Differential Evolution Based Dynamic Economic Dispatch with Nonsmooth Fuel Cost Function

*Dynamic economic dispatch (DED) is one of the major operational decisions in electric power systems. DED problem is an optimization problem with an objective to determine the optimal combination of power outputs for all generating units over a certain period of time in order to minimize the total fuel cost while satisfying dynamic operational constraints and load demand in each interval. This paper presents an improved differential evolution (IDE) method to solve the DED problem of generating units considering valve-point effects. Heuristic crossover technique and gene swap operator are introduced in the proposed approach to improve the convergence characteristic of the differential evolution (DE) algorithm. To illustrate the effectiveness of the proposed approach, two test systems consisting of five and ten generating units have been considered. The results obtained through the proposed method are compared with those reported in the literature.*

Keywords: Dynamic economic dispatch, ramp rate limits, nonsmooth fuel cost function, differential evolution

## 1. INTRODUCTION

Dynamic economic dispatch (DED) is an extension of the conventional economic dispatch problem used to determine the optimal generation schedule of on-line generators, so as to meet the predicted load demand over certain period of time at minimum operating cost under various system and operational constraints. Due to the ramp-rate constraints of a generator, the operational decision at hour t may affect the operational decision at a later hour. For a power system with binding ramp-rate limits, these limits must be properly modeled in production simulation. The DED is not only the most accurate formulation of the economic dispatch problem but also the most difficult dynamic optimization problem.

Most of the literature addresses DED problems with convex cost functions [1]–[3]. However, in reality, large steam turbines have steam admission valves, which contribute nonconvexity in the fuel cost function of the generating units [4]-[6]. Accurate modeling of DED problem will be improved when the valve point loadings in the generating units are taken into account. Furthermore, they may generate multiple local optimum points in the solution space. Previous efforts on solving DED problem have employed various mathematical programming methods and optimization techniques. Traditional methods like gradient projection method [1], Lagrangian relaxation [7], dynamic programming and so on, when used to solve DED problem, suffer from myopia for nonlinear, discontinuous search spaces, leading them to a less desirable performance and these methods often use approximations to limit complexity.

The stochastic search algorithms such as genetic algorithm (GA) [4],[8], evolutionary programming (EP) [5],[9],[10], simulated annealing (SA) [11], and particle swarm optimization (PSO) [6] may prove to be very effective in solving nonlinear ED problems

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without any restriction on the shape of the cost curves. They often provide a fast, reasonable nearly global optimal solution. The setting of control parameters of the SA algorithm is a difficult task and convergence speed is slow when applied to a real system. Though the GA methods have been employed successfully to solve complex optimization problems, recent research has identified some deficiencies in GA performance. This degradation in efficiency is apparent in applications with highly epistatic objective functions. Moreover, the premature convergence of GA degrades its performance and reduces its search capability that leads to a higher probability toward obtaining a local optimum [12]. EP seems to be a good method to solve optimization problems, when applied to problems consisting of more number of local optima the solutions obtained from EP method is just near global optimum one. Also GA and EP take long simulation time in order to obtain solution for such problems. All these methods use probabilistic rules to update their candidates positions in the solution space. Sequential quadratic programming (SQP) method seems to be the best nonlinear programming method for constrained optimization problem but the objective function to be minimized is nonconvex , it ensures the local optimum solution.

Recently, SA [13], hybrid EP-SQP [14], DGPSO [15] and hybrid PSO-SQP [16] methods are proposed to solve dynamic economic dispatch problem with nonsmooth fuel cost functions. These hybrid methods utilize local searching property of SQP along with stochastic optimization techniques to determine the optimal solution of DED problem.

Differential Evolution developed by Storn and Price is one of the excellent evolutionary algorithms [17] . 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. This paper develops an improved DE algorithm to determine the optimum generation schedule of the DED problem that takes into consideration of valve-point effects. In the proposed approach, the search capability of the DE algorithm is enhanced by introducing heuristic crossover operation and gene swap operator, which leads to a higher probability of getting global or near global optimal solutions. The proposed method is tested on five-unit and ten-unit sample test systems and the results are compared with a SA, hybrid EP-SQP, DGPSO and PSO-SQP methods. The effectiveness and potential of the proposed approach to solve DED problem is demonstrated.

## 2. FORMULATION OF DED PROBLEM

The classic DED problem minimizes the following incremental cost function associated to dispatchable units:

$$Min\ F = \sum_{t=1}^{T}\sum_{i=1}^{N} F_{it}(P_{it}) \quad (\$) \tag{1}$$

where $F$ is the total generating cost over the whole dispatch period, $T$ is the number of intervals in the scheduled horizon, $N$ is the number of generating units, and $F_{it}(P_{it})$ is the fuel cost in terms of its real power output $P_{it}$ at time $t$. Taking into account of the valve-point effects, the fuel cost function of $i^{th}$ thermal generating unit is expressed as the sum of a quadratic and a sinusoidal function in the following form

$$F_{it}(P_{it}) = a_i P_{it}^2 + b_i P_{it} + c_i + \left| e_i \sin(f_i (P_{i\min} - P_{it})) \right| \quad (\$/\text{h}) \tag{2}$$

where $a_{i,}$ $b_{i,}$ and $c_i$ are cost coefficients, $e_{i,} f_i$ are constants from the valve point effect of the $i^{th}$ generating unit, and $P_i$ is the power output of the $i^{th}$ unit in megawatts.

The minimization of the generation cost is subjected to the following equality and inequality constraints:

1) Real power balance constraint

$$\sum_{i=1}^{N} P_{it} - P_{Dt} - P_{Lt} = 0 \tag{3}$$

where $t = 1, 2, \ldots, T$. $P_{Dt}$ is the total power demand at time $t$ and $P_{Lt}$ is the transmission power loss at time $t$ in megawatts. $P_{Lt}$ is calculated using the $B$-Matrix loss coefficients and the general form of the loss formula using $B$-coefficients is

$$P_{Lt} = \sum_{i=1}^{N}\sum_{j=1}^{N} P_{it} B_{ij} P_{jt} \tag{4}$$

2) Real power generation limit

$$P_{i\min} \leq P_{it} \leq P_{i\max} \tag{5}$$

where $P_{imin}$ is the minimum limit, and $P_{imax}$ is the maximum limit of real power of the $i^{th}$ unit in megawatts.

3) Generating unit ramp rate limits

$$P_{it} - P_{i(t-1)} \leq UR_i, \qquad i = 1, 2, 3, \ldots\ldots\ldots, N \tag{6}$$

$$P_{i(t-1)} - P_{it} \leq DR_i \qquad i = 1, 2, 3, \ldots\ldots\ldots, N$$

where $UR_i$ and $DR_i$ are the ramp-up and ramp-down limits of $i^{th}$ unit in megawatts. Thus the constraint of (6) due to the ramp rate constraints is modified as

$$\max(P_{i\min}, P_{i(t-1)} - DR_i) \leq P_{it} \leq \min(P_{i\max}, P_{i(t-1)} + UR_i) \tag{7}$$

such that

$$P_{it,\min} = \max(P_{i\min}, P_{i(t-1)} - DR_i) \quad \text{and} \tag{8}$$

$$P_{it,\max} = \min(P_{i\max}, P_{i(t-1)} + UR_i)$$

4) Constraint satisfaction technique

To satisfy the equality constraint of equation (3), a loading of any one unit is selected as the depending loading $P_{Nt}$ . The power level of $N^{th}$ generator is given by

$$P_{Nt} = P_{Dt} + P_{Lt} - \sum_{i=1}^{(N-1)} P_{it} \tag{9}$$

The transmission loss $P_{Lt}$ is function of all the generators including that of dependent generator, and it is given by

$$P_{Lt} = \sum_{i=1}^{(N-1)} \sum_{j=1}^{(N-1)} P_{it} B_{ij} P_{jt} + 2P_{Nt} \left( \sum_{i=1}^{(N-1)} B_{Ni} P_{it} \right) + B_{NN} P_{Nt}^2 \tag{10}$$

Expanding and rearranging, equation (10) becomes

$$B_{NN} P_{Nt}^2 + \left( 2\sum_{i=1}^{(N-1)} B_{Ni} P_{it} - 1 \right) P_{Nt} + \left( P_{Dt} + \sum_{i=1}^{(N-1)} \sum_{j=1}^{(N-1)} P_{it} B_{ij} P_{jt} - \sum_{i=1}^{(N-1)} P_{it} \right) = 0 \tag{11}$$

The loading of dependent generator can be determined by solving (11) using standard algebraic method.

## 3. IMPROVED DIFFERENTIAL EVOLUTION ALGORITHM FOR DED PROBLEM

The detailed implementation of IDE to solve the dynamic economic dispatch problem, is as follows:

1) Initialization: DE uses NP D-dimensional parameter vectors

$$P_{k,G}; \quad k = 1,\ 2,\ 3, \ldots\ldots\ldots ,\ NP \tag{12}$$

in a generation *G*, with *NP* being constant over the entire optimization process. At the start of the procedure, i.e., generation $G = 1$, the population vectors have to be generated randomly within the limits. For *T* intervals in the generation scheduling horizon, there are *T* dispatches of generation by *N* generating units. An array of control variable vectors or positions of the each agent can be represented as

$$P_{k,G} = \left[ \left( P_{11}\ P_{21}\ P_{31}\ \cdots\ P_{N1} \right)\ \cdots\ \left( P_{1T}\ P_{2T}\ P_{3T}\ \cdots\ P_{NT} \right) \right], \quad \text{for} \quad k = 1, 2, 3, \ldots\ldots\ldots, NP \tag{13}$$

Where $P_{NT}$ is the generation power output of the $N^{th}$ unit at $T^{th}$ interval.

2) Heuristic Crossover operation: It is unique crossover operator because it uses values of the objective function in determining the direction of search and it produces only one offspring. The operator generates a single offspring $X_3$ from the randomly selected two parent vectors $X_1$ and $X_2$ in the population according to the rule

$$X_3 = r\ (X_2 - X_1) + X_2 \tag{14}$$

where *r* is a random number between 0 and 1 and the parent having higher fitness value is denoted by $X_1$ and lower $X_2$. The offspring produced due to crossover randomly replaces any one of the individuals in the population. A heuristic crossover operator with probability of 0.02 is implemented in this algorithm.

3) Mutation: For the following generation $G+1$, new vectors $V_{k,\ G+1}$ are generated according to the following mutation scheme

$$V_{k,G+1} = P_{k,G} + F \cdot (P_{r1,G} - P_{r2,G}), \quad \text{for} \quad k = 1, 2, 3, \ldots\ldots\ldots, NP \tag{15}$$

The integers *r1* and *r2* are chosen randomly over [1, NP] and should be mutually different from the running index *k*. Under certain circumstances, the index *k* will be exchanged by an arbitrary random number r3 $\in$ [1, NP]. *F* is a scaling factor, which controls the amplification of the differential variation. The value of scaling factor is defined as follows:

$$F = 1 - \frac{\text{iter}}{\text{itermax}} \tag{16}$$

where *iter* and *itermax* are the number of current iteration and the maximum iteration, respectively. In DE, the mutation is solely derived from positional information of current population. This scheme provides for automatic self-adaptation and eliminates the need to adapt standard deviations of a probability density function.

4) Evaluation of Each Agent: Each individual in the population is evaluated using the fitness function of the problem to minimize the fuel cost function. The real power limit of the first generator and the unit ramp rate limits are constrained by adding them as a exact penalty term to the objective function to form a generalized fitness function $f_k$ as given below.

$$f_k = \sum_{t=1}^{T}\sum_{i=1}^{N} F_{it}(P_{it}) + \sum_{t=1}^{T} \mu_1 \left|P_{1t} - P_{1t\lim}\right| + \sum_{t=2}^{T}\sum_{i=2}^{N} \mu_r \left|P_{it} - P_{r\lim}\right| \tag{17}$$

where $\mu_1$ *and* $\mu_r$ are penalty parameters, and

$$P_{1t\lim} = \begin{cases} P_{1\min}, & \text{if } P_{1t} < P_{1\min} \\ P_{1\max}, & \text{if } P_{1t} > P_{1\max} \\ P_{1t}, & otherwise \end{cases} \tag{18}$$

$$P_{r\lim} = \begin{cases} P_{i(t-1)} - DR_i, & \text{if } P_{it} < P_{i(t-1)} - DR_i \\ P_{i(t-1)} + UR_i, & \text{if } P_{it} > P_{i(t-1)} + UR_i \\ P_{it}, & otherwise \end{cases} \tag{19}$$

The penalty terms associated with inequality constraints are added to the objective function. The penalty terms reflect the violation of the constraints and assign a high cost of the penalty function to candidate point far from the feasible region.

5) Estimation and Selection: The parent is replaced by its child if the fitness of the child is better than that of its parent. Explicitly, the parent is retained in the next generation if the fitness of the child is worse than that of its parent. DE selection scheme is based on local competition only. i.e., a child $V_{k,\,G+1}$ will compete against one population member $P_{k,\,G}$ and survivor will enter the new population. The number *NT* of children which may be produced to compete against $P_{k,\,G}$ should be chosen sufficiently high so that sufficient number of child will enter the new population. if $V_{k,\,G+1}$ is worse than that of its parent , the vector generation process defined by (15) & (19) is repeated up to *NT* times. If $V_{k,\,G+1}$ still worse than that of its parent, $P_{k,\,G+1}$ will be set to $P_{k,\,G.}$ An insufficient number *NT* leads to

survival of too many old population vectors, which may induce stagnation. To prevent a vector $P_{k,\ G}$ from surviving indefinitely, DE employs the concept of aging. *NE* defines how many generations a population vector may survive before it has to be replaced due to excessive age. To this end $P_{k, G}$ in (13) is checked first for how many generations it has already lived. If $P_{k,\ G}$ has an age of less than NE generations it remains unaltered, otherwise $P_{i,\ G}$ is replaced by $P_{r3,\ G}$ with $r3 \neq k$ being a randomly chosen integer $r3 \in [1, NP]$. In short, if $P_{k,\ G}$ is too old it may not serve as a parent vector any more but will be replaced by a randomly chosen member of the current generation *G*.

6) Gene Swap operator: For a large scale optimization problems with difficult search spaces and lengthy chromosomes, the possibility of the DE algorithm to get trapped in local optima will be high. Maintaining diversity is especially important for dynamic optimization problems since the optimum of such a function changes over time and if the population is clustered in a tight region, the individuals may not be able to detect a change in the function landscape. In order to increase the diversity in the population of DE algorithm, a gene swap operator is introduced in the proposed algorithm. This operator randomly selects two genes in a chromosome and swaps their values. If the modified chromosome proved to have better fitness, it replaces original one in the new population. In the proposed algorithm, gene swap operator is applied with a probability of 0.05 that swaps the active power output of two units in the randomly selected individual.

7) Stopping Criterion: The procedure from 2-6 is repeated until the maximum number of iterations reached.

## 4. NUMERICAL SIMULATION RESULTS AND DISCUSSION

An improved DE algorithm for the DED problem described above has been applied to five-unit and ten-unit systems with nonsmooth fuel cost function to demonstrate the performance of the proposed method. The simulations were carried out on a PC with Pentium IV 2.8-GHZ processor. The software is developed using the MATLAB 6.5. An improved DE uses four control variables ie. population size *NP*, maximum number of generations *NG*, number of trials per iteration *NT*, number of generations a population vector may survive before it has to be replaced due to excessive age *NE*. The number of trials have been conducted with changes in the size of population, number of generations, and number of trials per iteration in order to obtain the best values to achieve the overall minimum cost of generation. The best solution obtained through the proposed method is compared to those reported in the recent literature.

Example-1: 5–unit system

The cost coefficients, generation limits, load demand in each interval and ramp-rate limits of five-unit sample system with valve-point loading are given in Appendix, which is taken from Ref. [13]. The scheduling time horizon is one day divided into 24 intervals. The transmission losses are calculated using B-coefficient loss formula. The results of the proposed method are compared with that of the simulated annealing (SA) method [13]. The IDE control parameters used in this example are $NP = 100$, $NG = 500$, $NT = 10$ and $NE = 5$. The optimal dispatch of real power for the given scheduling horizon using improved DE method is given in Table 1. The best total production cost obtained using proposed method is \$45800, compared to \$47356 of the SA method. The sum of total generating power in each interval satisfies the load demand plus transmission losses. The computation time taken by the algorithm is 3min, 17s.

Table 1 : Best scheduling of 5-unit system using improved DE method

| Hour | P1 (MW) | P2 (MW) | P3 (MW) | P4 (MW) | P5 (MW) | Ploss (MW) |
|---|---|---|---|---|---|---|
| 1 | 13.5391 | 99.3704 | 30.2998 | 127.1172 | 143.5164 | 3.8429 |
| 2 | 11.2817 | 98.5308 | 64.7365 | 124.7846 | 139.7971 | 4.1308 |
| 3 | 12.0242 | 105.7360 | 99.9374 | 125.0162 | 137.0990 | 4.8128 |
| 4 | 27.0177 | 106.5800 | 120.3798 | 125.2478 | 156.6716 | 5.8969 |
| 5 | 39.9826 | 99.3312 | 120.3491 | 124.9764 | 179.8703 | 6.5096 |
| 6 | 18.5381 | 111.6850 | 118.6123 | 137.7051 | 229.3824 | 7.9229 |
| 7 | 17.3986 | 94.4374 | 117.5525 | 174.9023 | 230.0848 | 8.3756 |
| 8 | 14.4462 | 99.2620 | 113.7126 | 211.2911 | 224.5312 | 9.2431 |
| 9 | 20.2907 | 99.2430 | 136.3110 | 210.9401 | 233.3671 | 10.1519 |
| 10 | 49.9993 | 101.3351 | 121.6219 | 210.4041 | 231.1839 | 10.5443 |
| 11 | 72.0943 | 103.7987 | 112.9096 | 209.4610 | 232.7864 | 11.0500 |
| 12 | 49.0762 | 95.2490 | 114.8818 | 210.0632 | 282.5364 | 11.8066 |
| 13 | 20.7067 | 97.9203 | 113.2666 | 211.2251 | 271.6483 | 10.7670 |
| 14 | 44.9018 | 101.9107 | 112.6850 | 211.5980 | 229.0945 | 10.1900 |
| 15 | 42.6234 | 106.1245 | 113.4645 | 210.1864 | 190.7303 | 9.1291 |
| 16 | 22.4686 | 98.0354 | 113.1596 | 210.1344 | 143.4480 | 7.2460 |
| 17 | 13.7916 | 100.0280 | 116.3379 | 194.7838 | 139.7523 | 6.6936 |
| 18 | 10.1286 | 97.0662 | 113.9712 | 210.3131 | 184.5040 | 7.9831 |
| 19 | 14.1660 | 99.0430 | 113.5148 | 203.6348 | 232.8794 | 9.2380 |
| 20 | 12.0689 | 98.6777 | 111.4379 | 209.7849 | 282.8782 | 10.8476 |
| 21 | 41.9365 | 86.6247 | 120.5802 | 195.4251 | 245.2676 | 9.8341 |
| 22 | 41.0368 | 76.6583 | 110.6187 | 166.3992 | 218.0152 | 7.7282 |
| 23 | 23.2548 | 92.1743 | 103.0519 | 130.8563 | 183.5350 | 5.8723 |
| 24 | 15.2391 | 70.2344 | 88.1839 | 130.7542 | 163.1208 | 4.5324 |

Example-2: 10–unit system

In this example, the DED problem of the 10-unit system is solved by the proposed method by neglecting transmission losses in order to compare the results of the improved DE method with hybrid methods such as Hybrid EP-SQP, Deterministically guided PSO and Hybrid PSO-SQP algorithms reported in literature [14], [15], & [16]. The load demand of the system was divided by 24 intervals. The system data for ten-unit sample system is taken from the Ref. [14] , as given in Appendix. Transmission losses have been ignored for the sake of comparison of results with those reported in literature. The following DE control parameters has been chosen for this example: $NP = 120$, $NG = 1500$, $NT = 10$, and $NE = 5$. The best results obtained through various hybrid methods and from the improved DE method are shown in Table 2. It clear from the table that the proposed method produces much better results compared to recently reported hybrid methods for solving DED problem. The optimum scheduling of generating units for 24 hours using proposed method is given in Table 3. The computation time of proposed method for ten-unit system is 14min, 15s. Figure 1 shows the convergence characteristics of the IDE for DED problem.

Table 2: Comparison of results for 10-unit system

| Method | Total fuel cost (dollars/24h) | Difference (%) from improved DE |
|---|---|---|
| Improved DE | 1026269 | --- |
| Hybrid EP-SQP[14] | 1031746 | 0.5306 |
| DGPSO[15] | 1028835 | 0.1494 |
| Hybrid PSO-SQP[16] | 1027334 | 0.1037 |

Table 3: Best scheduling of 10-unit system using improved DE method

| Hour | P1 (MW) | P2 (MW) | P3 (MW) | P4 (MW) | P5 (MW) | P6 (MW) | P7 (MW) | P8 (MW) | P9 (MW) | P10 (MW) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 226.653 | 135.010 | 232.146 | 60.155 | 73.031 | 57.000 | 129.995 | 47.006 | 20.005 | 55 |
| 2 | 226.843 | 135.030 | 305.610 | 60.137 | 73.000 | 57.540 | 129.813 | 47.027 | 20.001 | 55 |
| 3 | 303.957 | 150.391 | 312.253 | 60.046 | 122.743 | 57.000 | 129.603 | 47.000 | 20.007 | 55 |
| 4 | 303.351 | 229.524 | 331.327 | 60.035 | 172.743 | 57.039 | 129.975 | 47.006 | 20.001 | 55 |
| 5 | 302.830 | 309.507 | 337.410 | 60.001 | 122.762 | 95.439 | 129.996 | 47.006 | 20.049 | 55 |
| 6 | 379.834 | 389.487 | 338.729 | 60.188 | 73.016 | 135.264 | 129.467 | 47.009 | 20.005 | 55 |
| 7 | 379.967 | 459.959 | 302.114 | 75.387 | 73.006 | 159.999 | 129.523 | 47.022 | 20.021 | 55 |
| 8 | 379.841 | 396.569 | 339.865 | 124.731 | 122.964 | 159.983 | 129.991 | 47.000 | 20.057 | 55 |
| 9 | 456.523 | 397.284 | 339.842 | 174.728 | 172.960 | 130.739 | 129.917 | 47.006 | 20.000 | 55 |
| 10 | 456.582 | 459.983 | 338.274 | 211.290 | 222.960 | 130.908 | 129.994 | 47.003 | 20.005 | 55 |
| 11 | 456.444 | 459.996 | 339.832 | 255.159 | 222.712 | 159.850 | 129.983 | 47.010 | 20.014 | 55 |
| 12 | 465.802 | 459.793 | 339.511 | 299.877 | 242.993 | 159.996 | 129.974 | 47.007 | 20.047 | 55 |
| 13 | 457.002 | 459.997 | 300.751 | 257.028 | 222.503 | 122.856 | 129.844 | 47.018 | 20.001 | 55 |
| 14 | 380.226 | 396.844 | 305.844 | 207.145 | 222.744 | 159.786 | 129.399 | 47.006 | 20.006 | 55 |
| 15 | 303.669 | 390.425 | 339.992 | 157.603 | 172.744 | 159.820 | 129.618 | 47.129 | 20.001 | 55 |
| 16 | 302.696 | 310.449 | 286.680 | 107.634 | 172.215 | 122.332 | 129.987 | 47.001 | 20.006 | 55 |
| 17 | 379.823 | 230.498 | 260.451 | 61.008 | 172.642 | 123.557 | 129.999 | 47.002 | 20.020 | 55 |
| 18 | 380.774 | 310.259 | 300.307 | 60.420 | 172.515 | 151.611 | 129.990 | 47.125 | 20.000 | 55 |
| 19 | 380.458 | 390.118 | 300.653 | 71.348 | 221.933 | 159.925 | 129.428 | 47.137 | 20.000 | 55 |
| 20 | 456.353 | 459.884 | 339.993 | 121.252 | 223.660 | 159.003 | 129.987 | 77.127 | 49.742 | 55 |
| 21 | 380.012 | 459.916 | 335.361 | 76.326 | 237.966 | 122.307 | 129.986 | 107.125 | 20.002 | 55 |
| 22 | 303.007 | 382.899 | 261.195 | 60.745 | 222.631 | 72.543 | 129.901 | 119.997 | 20.083 | 55 |
| 23 | 229.435 | 304.436 | 181.198 | 61.010 | 172.717 | 58.245 | 129.955 | 119.994 | 20.011 | 55 |
| 24 | 293.992 | 224.469 | 101.208 | 60.285 | 122.725 | 57.102 | 129.988 | 119.228 | 20.002 | 55 |

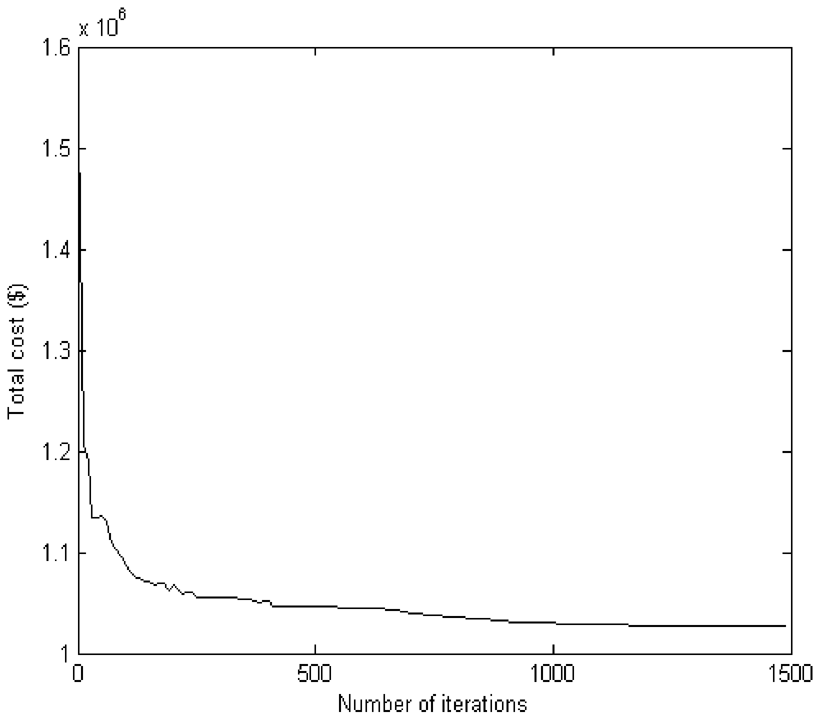


Fig. 1. Convergence characteristics of an improved DE method for 10-unit system.

## 5. CONCLUSION

An improved differential evolution based methodology has been developed for determination of optimal solution for DED problem with the generator constraints. The improved DE incorporates the heuristic crossover and gene swap operator to enhance its search capacity, which leads to a higher probability of getting the global or near global solution. The feasibility of the proposed method was demonstrated with five and ten-unit sample systems. The test results reveals that the optimal dispatch solution obtained through the improved DE lead to less operating cost than that found by other methods, which shows the capability of the algorithm to determine the global or near global solution for DED problem. The proposed approach outperforms SA, hybrid EP-SQP, DGPSO and PSO-SQP methods for DED problems in terms of quality of solution with better performance.

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**APPENDIX**

Table A: Data for the 5-unit system

| Quantities | Unit 1 | Unit 2 | Unit 3 | Unit 4 | Unit 5 |
|---|---|---|---|---|---|
| a ($/(MW)$^2$ h) | 0.0080 | 0.0030 | 0.0012 | 0.0010 | 0.0015 |
| b ($/MWh) | 2.0 | 1.8 | 2.1 | 2.0 | 1.8 |
| c ($/h) | 25 | 60 | 100 | 120 | 40 |
| e ($/h) | 100 | 140 | 160 | 180 | 200 |
| f (1/MW) | 0.042 | 0.040 | 0.038 | 0.037 | 0.035 |
| $P_{min}$ (MW) | 10 | 20 | 30 | 40 | 50 |
| $P_{max}$ (MW) | 75 | 125 | 175 | 250 | 300 |
| UR (MW/h) | 30 | 30 | 40 | 50 | 50 |
| DR (MW/h) | 30 | 30 | 40 | 50 | 50 |

Transmission Loss Coefficient for 5-unit system

$$B = \begin{bmatrix} 0.000049 & 0.000014 & 0.000015 & 0.000015 & 0.000020 \\ 0.000014 & 0.000045 & 0.000016 & 0.000020 & 0.000018 \\ 0.000015 & 0.000016 & 0.000039 & 0.000010 & 0.000012 \\ 0.000015 & 0.000020 & 0.000010 & 0.000040 & 0.000014 \\ 0.000020 & 0.000018 & 0.000012 & 0.000014 & 0.000035 \end{bmatrix} \text{ per MW.}$$

Table B: Load demand for 24 hours (5-unit system)

| Time (h) | Load (MW) | Time (h) | Load (MW) | Time (h) | Load (MW) | Time (h) | Load (MW) |
|---|---|---|---|---|---|---|---|
| 1 | 410 | 7 | 626 | 13 | 704 | 19 | 654 |
| 2 | 435 | 8 | 654 | 14 | 690 | 20 | 704 |
| 3 | 475 | 9 | 690 | 15 | 654 | 21 | 680 |
| 4 | 530 | 10 | 704 | 16 | 580 | 22 | 605 |
| 5 | 558 | 11 | 720 | 17 | 558 | 23 | 527 |
| 6 | 608 | 12 | 740 | 18 | 608 | 24 | 463 |

Table C: Data for the 10-unit system

| Quantities | Unit 1 | Unit 2 | Unit 3 | Unit 4 | Unit 5 |
|---|---|---|---|---|---|
| a ($/(MW)$^2$ h) | 0.00043 | 0.00063 | 0.00039 | 0.0007 | 0.00079 |
| b ($/MWh) | 21.60 | 21.05 | 20.81 | 23.90 | 21.62 |
| c ($/h) | 958.20 | 1313.6 | 604.97 | 471.60 | 480.29 |
| e ($/h) | 450 | 600 | 320 | 260 | 280 |
| f (1/MW) | 0.041 | 0.036 | 0.028 | 0.052 | 0.063 |
| $P_{min}$ (MW) | 150 | 135 | 73 | 60 | 73 |
| $P_{max}$ (MW) | 470 | 460 | 340 | 300 | 243 |
| UR (MW/h) | 80 | 80 | 80 | 50 | 50 |
| DR (MW/h) | 80 | 80 | 80 | 50 | 50 |

| Quantities | Unit 6 | Unit 7 | Unit 8 | Unit 9 | Unit 10 |
|---|---|---|---|---|---|
| a ($/(MW)$^2$ h) | 0.00056 | 0.00211 | 0.0048 | 0.10908 | 0.00951 |
| b ($/MWh) | 17.87 | 16.51 | 23.23 | 19.58 | 22.54 |
| c ($/h) | 601.75 | 502.70 | 639.40 | 455.60 | 692.40 |
| e ($/h) | 310 | 300 | 340 | 270 | 380 |
| f (1/MW) | 0.048 | 0.086 | 0.082 | 0.098 | 0.094 |
| $P_{min}$ (MW) | 57 | 20 | 47 | 20 | 55 |
| $P_{max}$ (MW) | 160 | 130 | 120 | 80 | 55 |
| UR (MW/h) | 50 | 30 | 30 | 30 | 30 |
| DR (MW/h) | 50 | 30 | 30 | 30 | 30 |

Table D: Load demand for 24 hours (10-unit system)

| Time (h) | Load (MW) | Time (h) | Load (MW) | Time (h) | Load (MW) | Time (h) | Load (MW) |
|---|---|---|---|---|---|---|---|
| 1 | 1036 | 7 | 1702 | 13 | 2072 | 19 | 1776 |
| 2 | 1110 | 8 | 1776 | 14 | 1924 | 20 | 2072 |
| 3 | 1258 | 9 | 1924 | 15 | 1776 | 21 | 1924 |
| 4 | 1406 | 10 | 2072 | 16 | 1554 | 22 | 1628 |
| 5 | 1480 | 11 | 2146 | 17 | 1480 | 23 | 1332 |
| 6 | 1628 | 12 | 2220 | 18 | 1628 | 24 | 1184 |