A NOVEL DIFFERENTIAL EVOLUTION ALGORITHM FOR ECONOMIC POWER DISPATCH PROBLEM

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Abstract. In power systems, Economic Power dispatch Problem (EPP) is an influential optimization problem which is a highly non-convex and non-linear optimization problem. In the current study, a novel version of Differential Evolution (NDE) is used to solve this particular problem. NDE algorithm enhances local and global search capability along with efficient utilization of time and space by making use of two elite features: self-adaptive control parameter and single population structure. The combined effect of these concepts improves the performance of Differential Evolution (DE) without compromising on quality of the solution and balances the exploitation and exploration capabilities of DE. The efficiency of NDE is validated by evaluating on three benchmark cases of the power system problem having constraints such as power balance and power generation along with nonsmooth cost function and is compared with other optimization algorithms. The Numerical outcomes uncovered that NDE performed well for all the benchmark cases and maintained a trade-off between convergence rate and efficiency.

1. Introduction. Taking power system into consideration, Economy Power dispatch Problem (EPP) is an important optimization problem [9] in which the main motive is the distribution of the total power demand among the various generators engaged and minimizing the total fuel cost of the system under several equality and inequality constraints. EPP has been solved by many traditional methods some of which are: linear programming, nonlinear programming, quadratic programming and newton-based methods etc. Usually, these methods work with the hypothesis that the fuel cost function of any generator is a simple convex function but practically, it could not always possible whereas generally, an EPP holds prohibited operating zones, ramp rate limit, value points and multiple fuel option. That’s why, the EPP is considered as a non-convex optimization problem which could not be handled by traditional methods.

During last few years, some evolutionary algorithms and swarm intelligence inspired algorithms such as genetic algorithm (GA) [17], differential evolution (DE) [10], evolutionary programming (EP) [30], particle swarm optimization (PSO) [11], biogeography-based optimization (BBO) [5] and chaotic bat algorithm [2] etc. have been implemented to deliver a solution for this multiconstrained economic power dispatch problem.

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2. Background and Motivation. Numerous studies have been drawn on this particular problem with different criteria. Besides, there are several improved algorithms proposed to provide a solution to this problem such as He et al. proposed a hybrid strategy of genetic algorithm with differential evolution to solve economic dispatch with valve-point effect [15]. A selforganizing hierarchical particle swarm optimization (SPSO) has been designed by Chaturvedi et al. [8]. Biswas et al. proposed a chemotactic differential evolution algorithm [6], which strengthens its global search ability. Safari et al. used iteration particle swarm optimization (IPSO) procedure for economic load dispatch with generator constraints [29] to prevent local optima problem. Then, the problem is solved with improved harmony search with wavelet mutation (IHSWM) proposed by Pandi et al. [24]. Rahmani et al. provided an evolutionary technique to initialize the population for particle swarm optimization (MPSO) [28].

Further, in order to enhance the efficiency of the algorithm, a hybrid method of particle swarm optimization and bacteria foraging algorithm with time-varying coefficient (HPSOTVAC) is developed by Abedinia et al. [1]. Qu et al. [27] and Zaman et al. [32] adopted evolutionary algorithms to solve EPP. Recently, an invasive weed optimization algorithm [12], an integrated approach based on artificial intelligence and novel meta-heuristic algorithms [13]-[14], an improved differential evolution algorithm [16], a novel quantum behaved particle swarm optimization algorithm [25] and Robust bi-level programming [20]-[22] have been delivered and worked well.

However, the major limitations of these methods are tuning the control parameter and efficient utilization of space and time due to which the algorithms may be sensitive to get stuck in the situations like premature convergence and local optima. Therefore, it is hard to find a feasible solution for nonlinear optimization problems which are multiconstrained. A Novel Differential Evolution (NDE) [26] algorithm is a variant DE algorithm [31] which is relatively a new population based stochastic search technique annexed to Evolutionary Algorithm (EA) to handle non-linear and complex optimization problem. DE is compact, easy to use, efficient and robust evolutionary algorithm. DE has also been applied to constrained problems [3], [23].

Gap research for this EPP is shown in Table 1 where it can be easily seen that different algorithms are applied on EPP different criteria and tests are drawn for different case studies as well. To get the quality solution, DE should be tuned with its control parameters. In Literature, the theory of self-adaptive control parameter has been adapted to overcome this situation of tuning the control parameters. Now a day, there are several variants of DE which are grounded on control parameter tuning to provide a solution to optimization problems; novel DE with self-adaptive parameter control [7], fuzzy adaptive-based variant of DE [19] and self-adaptive approach for parameter control of DE [18].

Therefore, this paper uses NDE [26] algorithm to solve EPP problems of power systems where NDE which adopts a new technique for controlling parameters (scaling factor F and crossover C_r) inlayed with single population frame applied to solve constrained optimization problems. Apart from previous research which has been discussed in the literature, the presented approach considers; a) Primarily a mathematical function is preserved to generate control parameter settings which will be passed to crossover and mutation operators to make it easily adopt these parameters, b) Single population structure which enhances the performance of the algorithm by reducing #FEs, memory space and CPU time consumption [4]. By
### Table 1. Survey on related work

| Reference | Problem                          | Algorithms                      | Case Study                                                                 |
|-----------|----------------------------------|---------------------------------|----------------------------------------------------------------------------|
| [17]      | ELD with valve point effect      | GA                              | 13 generating units                                                       |
| [30]      | ELD                              | EP                              | 3, 13, and 40 generating units                                            |
| [11]      | ELD with generator constraints   | PSO                             | 6, 15, and 40 generating units                                            |
| [15]      | ELD with valve-point effect      | HGA                             | 13 and 40 generating units                                                |
| [8]       | ELD                              | SPSO                            | 6, 15 and 40 generating units                                              |
| [6]       | ELD                              | CDE                             | 6 and 13 generating units                                                  |
| [5]       | ELD                              | BBO                             | 6, 10, 20 and 40 generating units                                          |
| [29]      | ELD with generator constraints   | IPSO                            | 6 and 15 generating units                                                  |
| [24]      | ELD                              | IHSWM                           | 40 generating units                                                       |
| [28]      | ELD                              | MPSO                            | 3, 6, 15, and 40 generating units                                          |
| [1]       | ELD                              | HPSOTVAC                        | 6, 15 and 38 generating units                                              |
| [10]      | Dynamic ELD                      | ADE                             | (1) 5-unit thermal system with Ploss for a 24-hours planning horizon;      |
|           |                                  |                                 | (2) 10-unit thermal system without Ploss for a 12-hours planning horizon;  |
|           |                                  |                                 | (3) 10-unit thermal system without Ploss for a 24-hours planning horizon;  |
| [2]       | ELD                              | CBA                             | 6, 13, 20, 40 and 160 generating units                                     |
| [32]      | Dynamic ELD                      | EA                              | (1) 5-unit thermal problems with and without Ploss;                       |
|           |                                  |                                 | (2) 10-unit thermal problems with and without Ploss;                      |
|           |                                  |                                 | (3) 7-unit hydro-thermal problem without Ploss;                           |
|           |                                  |                                 | (4) 19-unit solar-C-thermal system without Ploss;                         |
|           |                                  |                                 | (5) 6-unit wind-C-thermal system with Ploss                               |
| [27]      | Environmental/Economic Dispatch  | MOEA                            | (1) 6-generator 30-bus standard test system;                              |
|           |                                  |                                 | (2) 13-generator 57-bus system;                                           |
|           |                                  |                                 | (3) 3-generator system;                                                   |
|           |                                  |                                 | (4) 6-generator system;                                                   |
|           |                                  |                                 | (5) 14-generator 118-bus system;                                          |
|           |                                  |                                 | (6) 40-generator system;                                                  |
|           |                                  |                                 | (7) 10-generator system;                                                  |
| [16]      | Economic and Emission Dispatch   | IDE                             | 6 generating units                                                        |
| [25]      | ELD                              | QPSO                            | 6, 15 and 40 generating units                                              |
| [20]      | Renewable Energy Location        | Robust Bi-Level Programming      | Locating renewable energy sites                                           |
| This research | EPP                          | NDE                             | 6, 15 and 40 generating units                                              |

ELD: Economic Load Dispatch  
EPP: Economic Power dispatch  
GA: Genetic Algorithm  
EP: Evolutionary Programming  
PSO: Particle Swarm Optimization  
HGA: Hybrid Genetic Algorithm approach based on Differential Evolution  
SPSO: Self-organizing Hierarchical Particle Swarm Optimization  
CDE: Chemotactic Differential Evolution Algorithm  
BBO: Biogeography-Based Optimization  
IPSO: Iteration Particle Swarm Optimization  
IHSWM: Improved Harmony Search with Wavelet Mutation  
MPSO: Particle Swarm Optimization by Evolutionary Technique  
HPSOTVAC: Hybrid Particle Swarm Optimization with Time-Varying Acceleration Coefficients  
ADE: Automated Differential Evolution  
CBA: Chaotic Bat Algorithm  
EA: Evolutionary Algorithms  
MOEA: Multi-Objective Evolutionary Algorithms  
IDE: Improved Differential Evolution Algorithm  
SG-QPSO: Novel Quantum-Behaved Particle Swarm Optimization Algorithm  
NDE: Novel Differential Evolution
making use of these features of NDE, the proposed methodology works well on the EPP optimization problem.

The research paper is consolidated as: Section-3 elucidates the problem statement of economic power dispatch problem and provides a short introduction of parent DE algorithm whereas the details of adopted methodology along with constraint handling and the pseudo code of the NDE algorithm has been discussed in section-4. All experiment settings, results and analysis on three benchmark cases are inscribed in section-5. Later, the gist earned from the research study has been presented under section-6.

3. Problem Statement.

3.1. Economic Power Dispatch Problem. The main motive behind the EPP is to get an optimal fusion of the generators so that the total fuel cost i.e., the sum of cost function of each generator, can be minimized while satisfying several equality and inequality constraints associated with it. The mathematical formulation of the objective function for EPP is given below:

\[ \min F = \sum_{i=1}^{N} F_i(pwr_i), \]  

where \( F \) is the total fuel cost of the power system; \( pwr_i \) is the real power of \( i^{th} \) generator (in MW); \( N \) is the number of generators in the system; \( F_i \) is the fuel cost of the \( i^{th} \) generator which is generally represented in polynomial function as:

\[ F_i(pwr_i) = a_i(pwr_i)^2 + b_i(pwr_i) + c_i, \]  

where \( a_i, b_i \) and \( c_i \) are cost coefficients for \( i^{th} \) generating unit. In this context, the primary constraints are power balance constraint and power limit of generator constraints which are given below:

**Constraint 1: Power balance**
The generator power should be equal to total load demand plus total line losses.

\[ pwr_D + pwr_L - \sum_{i=1}^{N} pwr_i = 0, \]  

where \( pwr_D \) is total load demand (in MW); \( pwr_L \) is transmission loss (in MW). The transmission losses are represented as a quadratic function in terms of constant loss formula coefficient or B-coefficient and generators power [6] which are associated in the form,

\[ pwr_L = \sum_{i=1}^{N} \sum_{j=1}^{N} pwr_i B_{ij} pwr_j + \sum_{j=1}^{N} B_{0j} pwr_j + B_{00}, \]  

where \( B_{ij} \) is \( ij^{th} \) term of the loss coefficient square matrix; \( B_{0j} \) is the \( j^{th} \) term of the loss coefficient vector; \( B_{00} \) is the loss coefficient constant.

**Constraint 2: Power Generation**
Each generating unit has a minimum and maximum power generation limit. Therefore, the corresponding inequality constraints for \( i^{th} \) generator is defined as:

\[ pwr_i^{min} \leq pwr_i \leq pwr_i^{max}, \]
In the current study, ramp rate limit, prohibited operating zone and transmission losses are considered. At specific operating interval, the constraints of EPP are explained here:

- **Ramp-rate limit constraint**: To regulate the generator operation between two adjacent intervals, operating bounds for all active generating units need to satisfy the ramp-rate limit. The inequality ramp-rate constraint is,

\[
\max(p_{\text{min}}^i, p_{t-1}^i - DR_i) \leq p_t^i \leq \min(p_{\text{max}}^i, p_{t-1}^i + UR_i),
\]

where \(p_{\text{min}}^i\) and \(p_{\text{max}}^i\) are the present and the previous output power respectively; \(DR_i\) is the down-ramp limit and \(UR_i\) is the up-ramp limit for \(i^{th}\) generating unit (in MW/time period).

- **Prohibited operating zone constraint**: The feasible operating zone for the generating unit can be achieved by avoiding the prohibited area. The constraints are,

\[
p_{\text{low}}^{i,k} \leq p_t^i \leq p_{\text{low}}^{i,k+1} \\
p_{\text{up}}^{i,k} \leq p_t^i \leq p_{\text{max}}^i, \quad k = 2, 3, ..., z_i
\]

where \(p_{\text{low}}^{i,k}\) and \(p_{\text{up}}^{i,k}\) are lower and upper boundaries of \(k^{th}\) prohibited zone of \(i^{th}\) generating unit respectively while \(z_i\) is the number of prohibited zone of \(i^{th}\) generating unit. These are the constraints taken under consideration for this problem.

3.2. **Differential Evolution.** This section elucidates the parent DE algorithm \cite{31} in short. The working of DE starts with NP individuals in a population \(P\) as we do in other classical EAs. DE makes use of same mutation, crossover and selection operators as of classical EA operators to push the solution towards the optima.

At generation \(g\), the \(i^{th}\) randomly generated individual of the population will be represented as \(\vec{x}_g^i, (i = 1, ..., NP)\)

**Mutation**

As a prime operator of DE, mutation commenced working with three randomly selected candidate solutions which are exclusively distinct and got selected from the population at each generation \(g\) which then constructs a perturbed vector \(\vec{v}_g^i = (v_{1,i}, v_{2,i}, ..., v_{d,i})\) for each candidate solution of the current population. Mutation operator is given below:

\[
DE/rand/1 : \vec{v}_g^i = \vec{x}_g^a_1 + F \ast (\vec{x}_g^a_2 - \vec{x}_g^a_3),
\]

where \(1 \leq a1, a2, a3 \leq NP\) are randomly picked solutions with a restriction that, \(a1 \neq a2 \neq a3 \neq ai, \ 0 \leq F \leq 1\) is a control parameter called scaling factor and used to amplify difference vectors.

**Crossover**

In crossover phase, the trial vector \(\vec{u}_g^i = (u_{1,i}, u_{2,i}, ..., u_{d,i})\) for the current generation \(g\) is generated using the perturbed vector \(\vec{v}_g^i = (v_{1,i}, v_{2,i}, ..., v_{d,i})\) and target
vector \( \vec{x}_i^g = (x_{1,i}^g, x_{2,i}^g, \ldots, x_{d,i}^g) \). The working phenomenon is shown here:

\[
\begin{align*}
\vec{u}_j^g_{i} = & \begin{cases} 
\vec{v}_j_{i}^g & \text{if } \text{rand}_j \leq Cr \text{ or } j = j_{\text{rand}}, \\
x_{j,i}^g & \text{otherwise,}
\end{cases} 
\end{align*}
\]

(9)

where \( j = 1, \ldots, d, j_{\text{rand}} \in \{1, \ldots, d\} \) is produced randomly once for each value of \( i \). \( \text{rand}_j \) is defined as \( 0 < \text{rand}_j < 1 \), it is a uniformly distributed random number which will be generated for each \( j \) of the current generation and \( 0 \leq Cr \leq 1 \) is the crossover control parameter taken as per user’s choice.

**Selection**

This is the decision-making phase where it will be decided that using tournament selection process which vector will participate as a member of the population for next generation \( g + 1 \), whether it is the target vector \( \vec{x}_i^g \) or the corresponding trial vector \( \vec{u}_i^g \). It is defined as:

\[
\begin{align*}
\vec{x}_{i}^{g+1} = & \begin{cases} 
\vec{u}_i^g & \text{if } f(\vec{u}_i^g) \leq f(\vec{x}_i^g), \\
\vec{x}_i^g & \text{otherwise.}
\end{cases} 
\end{align*}
\]

(10)

This selection scheme makes sure that the candidates found are better or not worse than candidates of current population.

4. **Proposed Methodology.** Here, the phases of DE algorithm with modifications have been discussed in addition to the pseudo code of the proposed algorithm.

4.1. **Selection of control parameters.** As it is defined in literature that to get good quality solution, DE requires to fine-tune its control parameter’s value. In order to enhance the performance of parent DE, several self-adaptive variants are proposed in literature [7] to deal with unconstraint as well as constraint problem domain where it can be easily found that control parameter settings is a major aspect for designing an efficient DE algorithm. To find a suitable parameter setting for a particular problem is a tedious job.

For each iteration during evolution, a new strategy has been implemented to produce these parameter (\( F \) and \( Cr \)) values. The values of these parameters will be generated within a specified range of \([F_0, F_1]\) and \([Cr_0, Cr_1]\) respectively, which is set as \([0.1, 0.5]\) and \([0.5, 0.9]\) respectively. The mathematical model used for generation of \( F \) and \( Cr \) is as follows:

\[
F = \begin{cases} 
F_0 + r_1 + r_2 + r_3, & \text{if } P_F < r_4, \\
F_1, & \text{otherwise,}
\end{cases}
\]

(11)

\[
Cr = \begin{cases} 
Cr_0 + r_5, & \text{if } P_{Cr} < r_5, \\
Cr_1, & \text{otherwise,}
\end{cases}
\]

(12)

where, \( r_k \) is a uniformly generated random numbers and is defined as: \( r_k \in (0,1), \forall k \in 1, 2, 3, 4, 5 \). \( r \) is obtained by \( r = r_1 + r_2 + r_3/2 \). \( P_F \), scaling factor and \( P_{Cr} \), crossover probabilities are adjusted at value 0.5. As the values of \( F \) and
Cr may go beyond specified boundaries to keep the values within the specified boundaries, the bound conditions are as follows.

\[ F = \begin{cases} 
2 * F_0 - F, & \text{if } F < F_0, \\
2 * F_1 - F, & \text{if } F > F_1, 
\end{cases} \tag{13} \]

\[ Cr = \begin{cases} 
2 * Cr_0 - Cr, & \text{if } Cr < Cr_0, \\
2 * Cr_1 - Cr, & \text{if } Cr > Cr_1, 
\end{cases} \tag{14} \]

\( F \) and \( Cr \), evaluated for each and every iteration, directly affects the randomness of the solution reckoned post mutation and crossover operation. The major benefit of using this approach is that there is no need to make any guess and to predefine the parameter settings for any problem.

4.2. Single Population Structure. Babu and Angira [4] proposed the concept of single population. Current and advanced populations are maintained in parent DE simultaneously which eventually leads to higher \#FEs, CPU time consumption and extra memory. Whereas, only one population is preserved in single population structure based DE where candidate solutions are updated which are worse than or not good as the newly generated candidate solutions.

In case of parent DE algorithm, an advanced population is supported for this operation where these candidate solutions took part in mutation and crossover operation leading to next generation which gives rise to extramemory consumption. Whereas, in single population structure these newly generated candidate solutions can be entertained for participation in mutation and crossover operations for the current generation as well which is another striking feature of this methodology.

The interested reader may refer to Pooja et. al [26] for complete elucidation of NDE, where performance of NDE has been successfully demonstrated on constrained benchmark problems.

4.3. Constraint Handling. Evolutionary algorithms have been exercised successfully to solve several unconstrained optimization problems in past few decades. As, the mechanism to handle constrains is not provided with basic evolutionary algorithms which will force the search process towards feasible region. Therefore, EAs require extra efforts to play with constrains and be able to handle Constraint Optimization Problems (COPs). A number of researches have been conducted in the field of COP [3], [23].

In this study, Penalty function method as a constraint handling approach, which is quite simple and frequently used, has been taken under consideration. In this method, based on the weighted mean of constraint violation, the constrained problems are converted into unconstrained ones by adding or subtracting a penalty term to the objective function value. The exterior penalty function formulation is given by

\[ f' = f + \sum_{i=1}^{L} \sigma_i \text{Max}(0, g_i(x))^2 + \sum_{j=1}^{M} \lambda_j \text{Max}(0, |h_j(x)|)^2, \tag{15} \]

where \( \sigma_i \) and \( \lambda_j \) are taken as positive constant number and known as penalty factors. Usually, all equalities are transformed into inequalities using the inequality
given below; however, equality and inequality constraints can be handled by penalty function methods:

\(|h_j(x)| - \delta \leq 0\), where \(\delta\) is a small value and known as tolerance allowed.

4.4. **Pseudo Code of proposed NDE.** In this section the pseudo code of the proposed NDE algorithm has been demonstrated.

---

Initialize, initial population with respect to uniformly generated NP random solutions, \(P = \{\vec{x}_1^0, \vec{x}_2^0, ..., \vec{x}_i^0\}\).

\(x_{j,i} = \text{low}_j + \text{rand}(0,1) \times (\text{up}_j - \text{low}_j)\); where \(i = 1\) to \(NP\), \(j = 1\) to \(d\).

Evaluate \(f(\vec{x}_i^0)\).

According to the fitness value, sort the population.

*While (Termination criteria achieved)*

*For (i=1: NP)*

Randomly select three solutions \((\vec{x}_{a1}^0, \vec{x}_{a2}^0, \vec{x}_{a3}^0)\) which must be different from each other as well as from target vector, \(\vec{x}_i^0\).

Set the mutation factor \(F\) and crossover factor \(Cr\) values, according to the Eq. 11 and Eq. 12 respectively.

Maintain the values of control parameters \(F\) and \(Cr\) within the specified limits by using Eq. 13 and Eq. 14 respectively.

Perform Mutation and Crossover operations using Eq. 8 and 9 respectively.

Evaluate \(f(\vec{u}_i)\).

Select fittest candidate out of \(\vec{u}_i\) and \(\vec{x}_i\) which will be updated in the same population.

*End for loop*

Sort the population.

*End While loop*

---

5. **Experimental Settings.** The source code for EPP is fetched from the URL http://www.ntu.edu.sg/home/EPNSugan. The experiments are run on a computer with Intel(R) Core (TM) i3-2328M CPU@2.20GHz and RAM size is 4-GB.

5.1. **Parametric Settings.** All type of PC and parametric setting with performance measures for testing are given in section.

- Population size \(NP\) 100.
- \(P_F, P_{Cr}\) 0.5, 0.5 respectively for NDE.
- \(F, Cr\) 0.5, 0.9 respectively for DE [22]; Adapted using Eq. 11-14 for NDE.
- \(\delta\) \(10^{-4}\) [26].
- \(\sigma\) and \(\lambda\) \(10^5\) and \(10^3\).

All the algorithms, that are exercised to handle this problem, are executed thirty times for each case. However, the termination criteria for each run are predefined.

5.2. **Results and Discussion.** To show the exhibition of NDE [26], EPP is considered and validated on 6-unit, 15-unit and 40-unit power frameworks. The input information is taken from literature [6], [15] and (http://www.ntu.edu.sg/home/EPNSugan).
Case Study 1: 6-Unit Generator System

In this case study, we have taken six thermal power generating units with total demand of 1,263 MW. The cost coefficient with boundary value is listed in Table 2, while ramp rate with prohibited zones limits are given in Table 3. However, the coefficient matrix $B$ for transmission loss is given by:

$$
B_{ij} = 10^{-3} \begin{bmatrix}
1.7 & 1.2 & 0.7 & -0.1 & -0.5 & -0.2 \\
1.2 & 1.4 & 0.9 & 0.1 & -0.6 & -0.1 \\
0.7 & 0.9 & 3.1 & 0.0 & -1.0 & -0.6 \\
-0.1 & 0.1 & 0.0 & 2.4 & -0.6 & -0.8 \\
-0.5 & -0.6 & -1.0 & -0.6 & 12.9 & -0.2 \\
-0.2 & -0.1 & -0.6 & -0.8 & -0.2 & 15.0
\end{bmatrix}
$$

$$
B_{0i} = 10^{-3} \begin{bmatrix}
-0.3908 & -0.1297 & 0.7047 & 0.0591 & 0.2161 & -0.6635 \\
0.0056
\end{bmatrix}
$$

Table 2. Cost coefficient and bound values for 6-unit system.

| Unit no. | $a_i$ (MW) | $b_i$ (MW) | $c_i$ (MW) | $pwr_i^{\text{min}}$ (MW) | $pwr_i^{\text{max}}$ (MW) |
|----------|------------|------------|------------|-----------------|----------------|
| 1        | 0.007      | 7          | 240        | 100             | 500            |
| 2        | 0.0095     | 10         | 200        | 50              | 200            |
| 3        | 0.009      | 8.5        | 220        | 80              | 300            |
| 4        | 0.009      | 11         | 200        | 50              | 150            |
| 5        | 0.008      | 10.5       | 220        | 50              | 200            |
| 6        | 0.0075     | 12         | 190        | 50              | 120            |

Table 3. Ramp rate and prohibited zones limits for 6-unit system.

| Unit no. | $UR_i$ | $DR_i$ | $pwr_i(0)$ (MW) | Zone-1 | Zone-2 |
|----------|--------|--------|-----------------|--------|--------|
| 1        | 80     | 120    | 440             | 210-240| 350-380|
| 2        | 50     | 90     | 170             | 90-110 | 140-160|
| 3        | 65     | 100    | 200             | 150-170| 210-240|
| 4        | 50     | 90     | 150             | 80-90  | 110-120|
| 5        | 50     | 90     | 190             | 90-110 | 140-150|
| 6        | 50     | 90     | 110             | 75-85  | 100-105|

The experimental results obtained for 6-unit generating system is reported in Table 4. The results of NDE are compared with basic DE, GA [11] and PSO [11] in terms of mean fitness function, i.e., cost(/$/Hr) and total power loss of the system. It could be easily illustrated that in comparison to other algorithms, the proposed approach NDE acquired minimum cost for this particular benchmark case study. Total generated power obtained by NDE is 1,276.029 which is less than that of DE and GA. In this system, the mean total power loss observed is 15,448.48, which is also lower in comparison of other algorithms.

Case Study 2: 15-Unit generator System

This system includes 15 thermal power generating units, while the total load demand for this system is 2,630 MW. Input data for 15-unit system is given in Table 5-Table 6 [14].
Table 4. Experimental results of NDE, DE and other comparative algorithms for 6-unit system.

| Unit no. | NDE     | DE      | GA      | PSO     |
|----------|---------|---------|---------|---------|
| 1        | 441.8657| 460.7157| 474.8066| 447.497 |
| 2        | 169.6242| 172.7829| 178.6363| 173.3221|
| 3        | 249.2367| 259.1119| 262.2089| 263.4745|
| 4        | 139.5649| 142.234 | 134.2826| 139.0594|
| 5        | 160.22  | 165.8878| 151.9039| 165.4761|
| 6        | 105.0001| 88.735  | 74.1812 | 87.128  |

| $pwr_L$  | 13.0289 | 12.4673 | 13.0217 | 12.9584 |

Total output power 1,276.03 1,275.47 1,276.03 1,276.01

Min cost ($/hr) 15,444.09 15,449.48 15,459 15,450

Mean cost ($/hr) 15,448.48 15,452.28 15,469 15,454

Table 5. Cost coefficient and bound values for 15-unit system.

| Unit no. | $a_i$ (MW) | $b_i$ (MW) | $c_i$ (MW) | $pwr_i^{min}$ (MW) | $pwr_i^{max}$ (MW) |
|----------|------------|------------|------------|---------------------|--------------------|
| 1        | 0.000299   | 10.1       | 671        | 455                 | 150                |
| 2        | 0.000183   | 10.2       | 574        | 455                 | 150                |
| 3        | 0.001126   | 8.8        | 374        | 130                 | 20                 |
| 4        | 0.001126   | 8.8        | 374        | 130                 | 20                 |
| 5        | 0.000205   | 10.4       | 461        | 470                 | 150                |
| 6        | 0.000301   | 10.1       | 630        | 460                 | 135                |
| 7        | 0.000364   | 9.8        | 548        | 465                 | 135                |
| 8        | 0.000338   | 11.2       | 227        | 300                 | 60                 |
| 9        | 0.000807   | 11.2       | 173        | 162                 | 25                 |
| 10       | 0.001203   | 10.7       | 175        | 160                 | 25                 |
| 11       | 0.003586   | 10.2       | 186        | 80                  | 20                 |
| 12       | 0.005513   | 9.9        | 230        | 80                  | 20                 |
| 13       | 0.000371   | 13.1       | 225        | 85                  | 25                 |
| 14       | 0.001929   | 12.1       | 309        | 55                  | 15                 |
| 15       | 0.004447   | 12.4       | 323        | 55                  | 15                 |

The derived results of NDE for 15-unit generating system are elaborated in Table 7 in terms of mean fitness function, i.e., cost ($/Hr) and total power loss of the system which are also compared with DE, PSO [11], GA [11], IPSO [29] and MPSO [28]. As given in Table 7, NDE preserves total cost and total output power equals to $32,561.89 and 2,659.8923 MW respectively. Hence, it can be easily shown that in comparison to results drawn with other algorithms, the NDE obtained minimum cost. Total power loss in the system reported by NDE is 29.8923 which are also low in comparison to other algorithms except MPSO which gives second best performance by achieving total cost $32,569.9512. With the results, it is clear that NDE performed best among all considered algorithms.
Table 6. Ramp rate and prohibited zones limits for 15-unit system.

| Unit no. | UR_i | DR_i | pwr_i(0) | Zone-1  | Zone-2  | Zone-3  |
|----------|------|------|----------|---------|---------|---------|
| 1        | 180  | 120  | 400      | 150-150 | 150-150 | 150-150 |
| 2        | 180  | 120  | 300      | 185-255 | 305-335 | 430-450 |
| 3        | 130  | 130  | 105      | 20-20   | 20-20   | 20-20   |
| 4        | 130  | 130  | 100      | 20-20   | 20-20   | 20-20   |
| 5        | 80   | 120  | 90       | 180-200 | 305-335 | 390-430 |
| 6        | 80   | 120  | 400      | 230-255 | 335-395 | 430-455 |
| 7        | 80   | 120  | 350      | 135-135 | 135-135 | 135-135 |
| 8        | 65   | 100  | 95       | 60-60   | 60-60   | 60-60   |
| 9        | 60   | 100  | 105      | 60-60   | 25-25   | 25-25   |
| 10       | 60   | 100  | 110      | 25-25   | 25-25   | 25-25   |
| 11       | 80   | 80   | 60       | 20-20   | 20-20   | 20-20   |
| 12       | 80   | 80   | 40       | 30-40   | 55-65   | 20-20   |
| 13       | 80   | 80   | 30       | 25-25   | 25-25   | 25-25   |
| 14       | 55   | 55   | 20       | 15-15   | 15-15   | 15-15   |
| 15       | 55   | 55   | 20       | 15-15   | 15-15   | 15-15   |

Table 7. For 15-unit system (Experimental outcomes and comparison).

| Unit no. | NDE  | DE    | MPSO  | GA   | PSO  | IPSO  |
|----------|------|-------|-------|------|------|-------|
| 1        | 446.3316 | 454.998 | 455   | 415.31 | 455   | 455   |
| 2        | 366.7521 | 379.996 | 455   | 359.72 | 380   | 380   |
| 3        | 127.9874 | 129.9991 | 130   | 104.43 | 130   | 129.97 |
| 4        | 129.1781 | 129.9899 | 130   | 74.99  | 130   | 130   |
| 5        | 165.6126 | 169.9968 | 286.4128 | 380.28 | 170   | 169.93 |
| 6        | 423.1885 | 429.9944 | 460   | 426.79 | 460   | 459.88 |
| 7        | 415.0202 | 429.9944 | 465   | 341.32 | 430   | 429.25 |
| 8        | 132.9585 | 120.1228 | 60    | 124.79 | 60    | 60.43  |
| 9        | 124.8283 | 47.6016 | 25    | 133.14 | 71.05 | 158.02 |
| 10       | 82.68406 | 146.0069 | 37.5603 | 89.26  | 159.85 | 158.02 |
| 11       | 68.83981 | 79.99735 | 20    | 60.06  | 80    | 80     |
| 12       | 71.96576 | 79.9997 | 80    | 50     | 80    | 78.57  |
| 13       | 37.01169 | 25.0118 | 25    | 38.77  | 25    | 25     |
| 14       | 25.78839 | 16.8516 | 15    | 41.94  | 15    | 15     |
| 15       | 24.5418  | 20.6135 | 15    | 22.64  | 15    | 15     |

| Pow_L  | 29.8923 | 31.1792 | 28.9734 | 38.278 | 30.908 | 30.858 |
|---------|---------|---------|---------|--------|--------|--------|
| Total Output Power | 2,659.89 | 2,661.20 | 2,658.97 | 2,668.40 | 2,660.90 | 2,660.80 |
| Mean Cost ($/Hr) | 32,561.89 | 32,747.16 | 32,569.95 | 33,113 | 32,708 | 32,709 |

Case Study 3: 40-Unit generator System

This system considers 40 thermal power units and the total load requirement for this system is 10,500MW. This 40-unit system is a large and more nonlinear in nature. Therefore, it might achieve more local minima solutions and it is more complicated to get a solution as well as to reach the global optima solutions. Here, the Input data for 40-unit system is given in Table 8.
Table 8. Cost coefficient and bound values for 40-unit system.

| Unit no. | \( a_i \) (MW) | \( b_i \) (MW) | \( c_i \) (MW) | \( \text{pwr}_{\text{min}}^i \) (MW) | \( \text{pwr}_{\text{max}}^i \) (MW) |
|----------|----------------|----------------|----------------|-------------------------------|-------------------------------|
| 1        | 0.00708        | 9.15           | 1728.3         | 114                           | 36                            |
| 2        | 0.00313        | 7.97           | 647.85         | 114                           | 36                            |
| 3        | 0.00313        | 7.95           | 649.69         | 120                           | 60                            |
| 4        | 0.00313        | 7.97           | 647.83         | 190                           | 80                            |
| 5        | 0.00313        | 7.97           | 647.81         | 97                            | 47                            |
| 6        | 0.00298        | 6.63           | 785.96         | 140                           | 68                            |
| 7        | 0.00298        | 6.63           | 785.96         | 300                           | 110                           |
| 8        | 0.00284        | 6.66           | 794.53         | 300                           | 135                           |
| 9        | 0.00284        | 6.66           | 794.53         | 300                           | 135                           |
| 10       | 0.00277        | 7.1            | 801.32         | 300                           | 130                           |
| 11       | 0.00277        | 7.1            | 801.32         | 375                           | 94                            |
| 12       | 0.52124        | 3.33           | 1055.1         | 375                           | 94                            |
| 13       | 0.52124        | 3.33           | 1055.1         | 500                           | 125                           |
| 14       | 0.52124        | 3.33           | 1055.1         | 500                           | 125                           |
| 15       | 0.0114         | 5.35           | 148.89         | 500                           | 125                           |
| 16       | 0.0016         | 6.43           | 222.92         | 500                           | 125                           |
| 17       | 0.0016         | 6.43           | 222.92         | 500                           | 220                           |
| 18       | 0.0016         | 6.43           | 222.92         | 500                           | 220                           |
| 19       | 0.0001         | 8.95           | 107.87         | 550                           | 242                           |
| 20       | 0.0001         | 8.62           | 116.58         | 550                           | 242                           |
| 21       | 0.0001         | 8.62           | 116.58         | 550                           | 254                           |
| 22       | 0.0161         | 5.88           | 307.45         | 550                           | 254                           |
| 23       | 0.0161         | 5.88           | 307.45         | 550                           | 254                           |
| 24       | 0.0161         | 5.88           | 307.45         | 550                           | 254                           |
| 25       | 0.00313        | 7.97           | 647.83         | 550                           | 254                           |
| 26       | 0.00708        | 9.15           | 1728.3         | 550                           | 254                           |
| 27       | 0.00313        | 7.97           | 647.85         | 150                           | 10                            |
| 28       | 0.00313        | 7.95           | 649.69         | 150                           | 10                            |
| 29       | 0.00313        | 7.97           | 647.83         | 150                           | 10                            |
| 30       | 0.00313        | 7.97           | 647.81         | 97                            | 47                            |
| 31       | 0.00298        | 6.63           | 785.96         | 190                           | 60                            |
| 32       | 0.00298        | 6.63           | 785.96         | 190                           | 60                            |
| 33       | 0.00284        | 6.66           | 794.53         | 190                           | 60                            |
| 34       | 0.00284        | 6.66           | 794.53         | 200                           | 90                            |
| 35       | 0.00277        | 7.1            | 801.32         | 200                           | 90                            |
| 36       | 0.00277        | 7.1            | 801.32         | 200                           | 90                            |
| 37       | 0.52124        | 3.33           | 1055.1         | 110                           | 25                            |
| 38       | 0.52124        | 3.33           | 1055.1         | 110                           | 25                            |
| 39       | 0.52124        | 3.33           | 1055.1         | 110                           | 25                            |
| 40       | 0.0114         | 5.35           | 148.89         | 550                           | 242                           |
In Table 9, the results of NDE are captured and compared with respect to DE, IHSWM [24], HPSOTVAC [1], SPSO [8] and BBO [5] for EPP 40-unit generating system. However, in this case study, it can be easily observed that the average cost obtained by NDE is $1,21,992.2 which is less than that obtained by DE and SPSO. Similarly, NDE gives promising results in terms of minimum fitness value as compared to that observed with other comparative algorithms. Total output power obtained by NDE is 10,500MW which means that there is no power loss in the system. Similarly, IHSWM, HPSOTVAC and SPSO give the same results in terms of power loss.

Table 9. For 40-unit system (Experimental outcomes and comparison).

| Unit no. | NDE   | DE   | IHSWM | HPSOTVAC | SPSO | BBO   |
|----------|-------|------|-------|----------|------|-------|
| 1        | 90.59008 | 113.035 | 113.9088 | 113.9907 | 113.97 | 110.8158 |
| 2        | 160.0214 | 180.7317 | 179.7332 | 175.0364 | 179.77 | 179.7549 |
| 3        | 81.69155 | 87.3028 | 88.7117 | 91 | 97 | 88.20832 |
| 4        | 107.7849 | 110.2516 | 139.9992 | 140 | 91.01 | 139.9866 |
| 5        | 278.066 | 259.0112 | 259.6372 | 260.3635 | 259.87 | 259.935 |
| 6        | 268.3649 | 284.6521 | 284.6106 | 288.1256 | 286.99 | 284.6749 |
| 7        | 95.41785 | 96.508 | 97.402 | 120 | 109.19 | 97.40261 |
| 8        | 160.0214 | 180.7317 | 179.7332 | 175.0364 | 179.77 | 179.7549 |
| 9        | 81.69155 | 87.3028 | 88.7117 | 91 | 97 | 88.20832 |
| 10       | 228.3208 | 131.3615 | 130 | 130 | 204.05 | 130.0298 |
| 11       | 286.0884 | 243.8422 | 168.7992 | 170 | 94 | 94.01459 |
| 12       | 309.307 | 302.4883 | 214.7593 | 210.0287 | 212.3 | 212.3472 |
| 13       | 346.2984 | 394.1255 | 394.2774 | 390.0677 | 393.76 | 394.264 |
| 14       | 354.3069 | 394.3787 | 394.2762 | 300.0056 | 392.05 | 392.2472 |
| 15       | 442.9098 | 489.715 | 489.2787 | 487.0486 | 489.49 | 489.2737 |
| 16       | 440.5635 | 492.2923 | 489.2787 | 485.0793 | 489.35 | 489.3047 |
| 17       | 503.2849 | 516.0751 | 511.2827 | 510.541 | 512.39 | 512.3087 |
| 18       | 481.891 | 512.4736 | 511.2768 | 511.3472 | 512.19 | 512.3495 |
| 19       | 506.4365 | 506.0514 | 504.5207 | 507.6247 | 503.62 | 503.5057 |
| 20       | 496.2304 | 524.5663 | 523.2794 | 526 | 523.65 | 523.3144 |
| 21       | 512.3193 | 524.3457 | 523.4772 | 523.9211 | 523.06 | 523.3629 |
| 22       | 511.7555 | 524.2132 | 523.2928 | 525.612 | 520.72 | 523.2883 |
| 23       | 507.4037 | 525.7952 | 523.3047 | 521.02 | 524.86 | 524.2989 |
| 24       | 493.267 | 522.6361 | 523.2762 | 520.1457 | 525.22 | 523.2802 |
| 25       | 10.30096 | 10.1786 | 10 | 10 | 10 | 10.0281 |
| 26       | 19.53625 | 12.3112 | 10.0022 | 10 | 10 | 10.00321 |
| 27       | 87.11869 | 90.3572 | 88.362 | 89.7002 | 87.64 | 87.1459 |
| 28       | 184.1883 | 187.5783 | 190 | 190 | 190 | 189.9913 |
| 29       | 174.4745 | 167.4291 | 190 | 190 | 190 | 189.9888 |
| 30       | 169.4674 | 177.3801 | 189.9935 | 190 | 190 | 189.9998 |
| 31       | 171.0925 | 166.2373 | 164.7992 | 167.0209 | 200 | 164.8542 |
| 32       | 176.4929 | 185.5927 | 164.8923 | 200 | 167.18 | 192.9576 |
| 33       | 172.1041 | 173.4381 | 164.864 | 200 | 172.12 | 199.9876 |
| 34       | 94.5799 | 89.3767 | 110 | 110 | 110 | 109.9941 |
| 35       | 85.26457 | 91.0112 | 110 | 110 | 110 | 109.9992 |
| 36       | 93.85836 | 91.6815 | 109.9965 | 110 | 95.58 | 109.9833 |
| 37       | 83.38011 | 512.0169 | 511.2828 | 511.0323 | 510.85 | 511.2794 |

| Powloss | 0 | 0.001 | 0 | 0 | 0 | 0.28 |
|----------|---|-------|---|---|---|-----|
| Total Output Power | 10,500.00 | 10,500.00 | 10,500.00 | 10,500.00 | 10,500.00 | 10,500.28 |
| Min Cost ($/Hr) | 1,21,721.62 | 1,21,974.50 | 1,21,416.26 | 1,21,070.64 | 1,22,049.66 | 1,21,479.50 |
| Mean Cost ($/Hr) | 1,21,992.20 | 1,22,580.30 | 1,21,553.42 | 1,21,075.74 | 1,22,327.36 | 1,21,512.05 |
Figure 1. Convergence graph between total cost and #FE for EPP: (a) 6-unit generating system, (b) 15-unit generating system, (c) 40-unit generating system.

The experimental outcomes obtained for 6, 15 and 40-unit generating system are reported in Table 4, 7 and 9 respectively. Also, the convergence graph of NDE and DE for 6, 15 and 40-unit generating system is drawn in Figure 1 with respect to their convergence speed where it can be easily observed that NDE is more efficient in comparison to DE in terms of convergence speed also.

6. Conclusion. In the present study, a Novel DE variant named as NDE is used to handle the complex mathematical real-life problems i.e., EPP. For population based stochastic search techniques like DE, this problem is very challenging. NDE worked very effectively as compared to other algorithm for all three benchmark cases. Numerical experiments show very competitive results and gives best performance in terms of total output power and loss of power in the system. It can be concluded that NDE proved to be very effective and efficient tool for real life optimization problems as shown with the achieved results. The application of NDE on EPP with value point effect and other industrial problems will be focused in future.
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