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RESEARCH ARTICLE

Hybrid DE-NSO for Multi Type Economic Load Dispatch Problem (Economic Load Dispatch: An Approach using Differential Evolution Algorithm with Neighborhood Search Operator)

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ABSTRACT

This paper discusses a novel and efficient algorithm to solve Economic Load Dispatch Problem (EDP) constructed with a non-smooth fuel cost function. Due to non-linear generator constraints such as prohibited operating zones, valve point loading and spinning reserve, optimization problem arises in the formulation of more realistic EDP. To solve this complex limitations of EDP, a new technique known as Differential Evolution (DE) is proposed in which a Neighborhood Search Operation (NSO) is performed for each population member, which is accelerated towards finding the global solution. The weak solutions are replaced by randomly selected individuals thus exploring the search space for new optimum regions. The main concept of this method is to stabilize the exploitation and exploration ability of DE. Thus a method known as NSO-DE is proposed such that, DE runs as the main optimizer while NSO fine tunes the solution and acts as a local optimizer. The effective and robust characteristics of the proposed NSO-DE method is evaluated based on three standard test EDP cases comprising 10, 13 and 15 thermal units. Based on the quality of obtained final solution, performance comparison with other DE methods is done.

Keywords: Economic load dispatch, Prohibited operating zone, Spinning reserve, Differential evolution, Neighborhood search operator.

1. INTRODUCTION

Due to increase in the cost of power generation, shortage in energy resources and increasing demand in electric energy, performing optimal economic dispatch in power operating system is in need. Economic Load Dispatch (ELD) helps to reduce the power generation cost which is very high especially in fossil fuel plants. The main objective of ELD is to assign the generated power to the committed units, thereby the utilized fuel cost is minimized by satisfying all the required constraints [1, 2].

Traditionally in ELD problems, the generating unit fuel-cost function constructed as quadratic function is resolved using certain derivative based optimization techniques which includes lamda iteration method, base point and participation factor method, gradient method, Newton method [3], dynamic programming [4], linear programming, nonlinear programming and quadratic programming methods [5, 6]. The fuel-cost curve is assumed to be monotonically increasing piecewise-linear functions. At certain times, this assumption produces infeasible solution due to nonlinear characteristics such as discontinuous operating zones, ramp rate limits, and non-convex cost functions [7, 8].

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In prohibited operating zones, the operating region is divided into a number of isolated sub-regions [9]. It can only be dispatched to one of the isolated sub-regions in practical operation. Each sub region forms a multiple decision spaces to determine the optimal economic dispatch [10]. Large generating units consisting of a multi-valve steam turbine include several admission valves, which are opened in a sequential manner to attain increased unit output. EDP modelling with these valve point effects results in sinusoidal effect on the cost curve [11]. Modelling EDP with these practical characteristics of generating units leads to the transformation of EDP to a complex optimization problem with non-convex factors and multiple minima, thus making it difficult for conventional derivative based optimization method to find out the global optimum. To overcome the limitations of non-convex complex EDP, a derivative-free optimization methods named as Genetic Algorithms (GAs) [12, 13], Simulated Annealing (SA) [14], Tabu Searches (TS), Artificial Neural Networks (ANNs) [15], Particle Swarm Optimization (PSO) [16, 17] and DE [18] are introduced in replacement of mathematical approach. These algorithms are in the form of probabilistic heuristics, with global search properties. The genetic algorithm operates faster comprising of parallel search features. But, owing to premature convergence, performance degrades and minimizes the searching capability thus acquiring high probability local optimum [19-23]. Alike GA, PSO also converges prematurely that may exist when the particle and group best solutions are trapped into local minimums during the search process [24-26].

Localization occurs due to which the particles tend to fly to local or near local optimums, thus concentrating in a small area and in turn weakens the global exploration ability. DE has simple structure and local searching property. It works faster and is easy to use. But its greedy updating principle and intrinsic differential property usually lead the computing process to be trapped at local optima [27]. In DE, the fittest of an offspring competes one by one with that of the corresponding parent, which differs from other Evolutionary Algorithms (EAs). This one by one competition gives rise to a faster convergence rate leading to a higher probability of obtaining a local optimum, as the diversity of the population descends faster during the solution process. To overcome this, DE is presented with NSO [28] which balances the effect of two contradictory aspects such as exploration and exploitation. NSO provides a proper trade-off between the exploration and exploitation ability to DE. Thus this method explores a better valley of solution during the progress of each run which improves the performance of the probabilistic method, thereby increasing the possibility of exploring the global solution.

In this paper, DE combined with NSO is proposed to solve non-smooth EDP consisting of 10, 13 and 15 generating units. The EDPs with incremental fuel cost functions considering the valve-point loading effects are tested and the comparison results are provided with the other DE variants, validating the performance of the present work.

2. FORMULATION OF NON-SMOOTH ELD

In general, the classic EDP can be constructed as an optimization process with the objective function as given in (2.1).

$$\min F_T = \left(\sum_{i=1}^{N} F_i\,(P_i)\right) \tag{2.1}$$

This objective function represents N generating unit power system, each loaded to P_iMW. The generating units are loaded such that the total Fuel Cost (FT) can be reduced by satisfying the power balance and other constraints of the system.

F_i represents the cost function related to fuel input-power output of i-th unit. The simplified cost function $F_i(P_i)$ for generator unit i loaded with P_iMW is constructed based on quadratic equation given by (2.2).

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i \tag{2.2}$$

where a_i, b_i and c_i denote the fuel cost coefficients of the i-th generating unit.

Practically, multi-valve steam turbine generating unit possess input-output curve different from smooth cost function. By incorporating the loading effects of valve point, the incremental fuel cost function is expressed as in (2.3).

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i + \cdots + \left|e_i * \sin\left\{f_i * \left(P_i^{min} - P_i\right)\right\}\right| \tag{2.3}$$

In the above equation, e_i and f_i denote the i-th generator coefficients due to valve-point effects. The added sinusoidal term in (2.3) forms ripples to heat-rate valve thereby introducing local minima to search space.

The objective function of EDP subjected to operating constraints of power system is represented in (2.4).

$$\sum_{i=1}^{N} P_i - P_D - P_L = 0 \tag{2.4}$$

$$P_{imin} \leq P_i \leq P_{imax} \tag{2.5}$$

where P_D denotes the total load demand and P_L signifies the total transmission loss. P_{imin} and P_{imax} specify the minimum and the maximum power outputs of i-th unit.

Considering the generator ramp rate limits, the operating limits of (2.5) is expressed in (2.6).

$$\max\left(P_i^{min}, P_{i0} - DR_i\right) \leq P_i \dots \dots \leq \min(P_i^{max}, P_{i0} - UR_i) \tag{2.6}$$

where P_{0i} is the previous output power, UR_i and DR_i is the up ramp and down ramp limit of the i-th generating unit.

Due to certain limitations like faults in machine or auxiliary equipment, generating unit experiences prohibited operating zones, which undergo amplifications of vibration in their shaft bearing. To prevent operation in these zones, the units have discontinuous input-output characteristics as in (2.7).

$$P_i \in \left\{ \begin{matrix} P_{i,min} \leq P_i \leq P_{i,1}^{l} \\ P_{i,k-1}^{u} \leq P_i \leq P_{i,k,}^{l}\ k = 2, 3, \dots, p_{zi} \\ P_{i,p_{zi}}^{u} \leq P_i \leq P_{i,max,}^{l}\ i = 1, 2, \dots, n_{pi} \end{matrix} \right\} \tag{2.7}$$

where n_{pz} denotes the number of prohibited zones for unit i, $P_{i,k}^{l}$ and $P_{i,k}^{u}$ indicate the lower and upper bounds of k-th prohibited zone of i-th generating unit.

$$\sum_{i \in \psi} S_i \leq S_R \tag{2.8}$$

$$S_i = \min\{(P_{imax} - P_i), S_{imax}\} \forall \in (\psi - \varphi) \tag{2.9}$$

$$S_i = 0\ \forall_i \in \psi \tag{2.10}$$

where the parameters in (2.8), (2.9) and (2.10) are described as follows. S_i represents the spinning reserve of unit i, S_R specifies the spinning reserve requirement of system, P_{imax} indicate the maximum generation limit of unit i, S_{imax} denotes the maximum spinning reserve of unit i and Ψ is considered as a set of all units with prohibited zones.

3. NSO

NSO is modeled by developing a neighborhood structure and a global and local mutation operator as explained below.

3.1. Neighborhood model

[29, 30] Variation and selection processes drive the DE population evolution. The variation process enables to explore several search space regions whereas the selection process confirms the exploitation of previous knowledge about the fitness landscape. The classical DE faces premature convergence problem, in which the population is converged to local optima of a multimodal objective function thereby losing its diversity. Also this algorithm stops finding any better solutions during its progress, even though a new individual penetrates the population. DE stops proceeding towards the global optimum resulting in stagnation where the population will not converge to a local optimum or any point. Similar to other evolutionary computing algorithms, DE performance degrades as the search space dimension grows.

In this paper, a hybrid method is proposed to integrate the exploration and exploitation ability of DE by balancing their effects. The explorative mutation operator known as global mutation model possess greater chance to locate the minima of the objective function but it requires more generations or iterations whereas the exploitative mutation operator known as local mutation model converges immediately to a minimum of the objective function. But this operator faces the problem of premature convergence to produce a suboptimal solution.

Two types of neighborhood models such as local neighborhood and global mutation models are proposed. In local neighborhood model, the best position vector is mutated from a small neighborhood not depending on the entire population whereas in global mutation model, the mutation is performed based on globally best vector $\vec{X}_{best,G}$ of entire population, where G denotes the current generation.

A vector's neighborhood is the set of other connected parameter vectors, which considers their experience while upgrading its position. The interconnected graph forms the neighborhood structure and is independent of the position indicated by the vectors. In the local model, when the parameter vector seems to point a good region of search space, its immediate neighbour is influenced directly.

3.2. Local and global neighborhood

The best fittest vector (local donor vector) and other two vectors are generated from the same neighbourhood of each population member modelled as in (3.1).

$$\vec{L}_{i,G} = \vec{X}_{i,G} + \alpha \cdot \left(\vec{X}_{n\_best_i,G} - \vec{X}_{i,G}\right) \ldots \beta \cdot \left(\vec{X}_{p,G} - \vec{X}_{q,G}\right) \quad (3.1)$$

where the subscript n_best_i indicates the best vector in the neighborhood of $\vec{X}_{i,G}$ and p, q ∈ [i - k, i + k] with the assumption $p \neq q \neq i$.

The global donor vector is also generated similarly as in (3.2).

$$\vec{g}_{i,G} = \vec{X}_{i,G} + \alpha \cdot \left(\vec{X}_{g_{best},G} - \vec{X}_{i,G}\right) \ldots \beta \cdot \left(\vec{X}_{r1,G} - \vec{X}_{r2,G}\right) \quad (3.2)$$

where the subscript gbest indicates the best vector in the entire population at generation G and $r_1, r_2 \in [1, NP]$ with $r_1 \neq r_2 \neq i$ α and β are the scaling factors. The above two mutation operators are integrated using a parameter known as weight factor. Here, the global and local donor vectors are integrated using a scalar weight ω ∈ (0, 1) forming the actual donor vector of this algorithm as given in (3.3).

$$\vec{V}_{i,G} = \omega \cdot \vec{g}_{i,G} + (1-\omega) \cdot \vec{L}_{i,G} \quad (3.3)$$

4. DE WITH NSO

DE starts with a population of NP D-dimensional parameter vectors representing the candidate solutions. Since the parameter vectors are likely to be changed over different generations, we may adopt the following notation for representing the i-th vector of the population at the current generation as defined in (4.1).

$$\vec{X}_{i,G} = \left[x_{1,i,G}, x_{2,i,G}, \ldots\ldots, x_{D,i,G}\right] \quad (4.1)$$

The subsequent generations in DE is denoted by G = 0, 1, 2,…, G_{max}. The initial population (at G = 0) should cover the entire search space as much as possible by uniformly randomizing individuals within the search space constrained by the prescribed minimum and maximum bounds. The j-th component of the i-th vector is given in (4.2).

$$x_{j,i,0} = x_{j,min} + rand_{i,j}(0,1) \ldots \left(x_{j,max} - x_{j,min}\right) \quad (4.2)$$

where $rand_{i,\,j}$ (0, 1) is a uniformly distributed random number lying between 0 and 1 and is instantiated independently for each component of the i -th vector. Then mutation, crossover, and selection process are carried out.

4.1. Mutation

The vector indices are sorted randomly in order to preserve the diversity of each neighborhood. For every vector $\vec{X}_{i,G}$ a neighborhood of radius k consisting of vectors $\vec{X}_{i-k,G}, \ldots \vec{X}_{i,G}, \ldots \vec{X}_{i+k,G}$ is defined. The vectors are arranged on a ring topology with respect to their indices and they are considered as static.

After initialization, DE creates a donor vector $\vec{V}_{i,G}$ corresponding to each population member or target vector $\vec{X}_{i,G}$ in the current generation through mutation. In this method, the actual donor vector is created with the help of global and neighborhood model.

For each member, a global and local donor vector is created using (3.1) and (3.2). And they are combined using a scalar vector ω as given in (4.3)

$$\vec{V}_{i,G} = \omega \cdot \vec{g}_{i,G} + (1-\omega) \cdot \vec{L}_{i,G} \quad (4.3)$$

4.2. Crossover

Binomial crossover is executed on each D variable when the random number between 0 and 1 is found to be less than or equal to Cr value. Also, the parameters devised from the donor follows a binomial distribution denoted as in (4.4).

$$U_{j,i,G} = \begin{cases} v_{j,i,G}, & \text{if}(\text{rand}_{i,j}(0,1) \leq Cr \\ x_{j,i,G}, & \text{otherwise} \end{cases} \quad (4.4)$$

where $\text{rand}_{i,j}$ (0, 1) ∈ [0, 1] denotes a random number distributed uniformly forming a new vector for each j-th component of the i-th parameter vector. J_{rand} ∈ [1, 2,....,D] denotes the index chosen randomly to ensure at least one component from $\vec{v}_{i,G}$.

4.3. Selection

To keep the population size constant over subsequent generations, the next step of the algorithm calls for selection to determine whether the target or the trial vector survives to the next generation i.e., at G = G + 1. The selection operation is described in (4.5).

$$\vec{x}_{i,G+1} = \begin{cases} \vec{U}_{i,G}, & \text{if } f\left(\vec{U}_{i,G}\right) \leq f\left(\vec{x}_{i,G}\right) \\ \vec{x}_{i,G}, & \text{if } f\left(\vec{U}_{i,G}\right) \geq f\left(\vec{x}_{i,G}\right) \end{cases} \quad (4.5)$$

where $f\left(\vec{x}\right)$ is the function to be minimized. So if the new trial vector yields an equal or lower value of the objective function, it replaces the corresponding target vector in the next generation; otherwise the target is retained in the population. Hence the population either gets better (with respect to the minimization of the objective function) or remains the same in fitness status, but never deteriorates.

5. PSEUDO CODE FOR DE-NSO

The pseudo code for DE with NSO is given as,

Step 1. Set the generation number G = 0 and randomly initialize the population of NP individuals, $P_G = \left\{\vec{x}_{i,G}, \ldots, \vec{x}_{NP,G}\right\}$ with $\vec{x}_{i,G} = \left[\vec{x}_{1,i,G}, \vec{x}_{2,i,G}, \vec{x}_{3,i,G}, \ldots, \vec{x}_{D,i,G}\right]$ and $\left[\vec{x}_{min}, \vec{x}_{max}\right]$ with i=[1, 2, 3, ….NP].

Step 2. WHILE the stopping criterion is not satisfied

DO

FOR i=1 to NP

Step 2.1. Mutation step

Generate a donar vector,

$$\vec{v}_{i,G} = \left\{\vec{v}_{1,i,G}, \vec{v}_{2,i,G} \ldots, \vec{v}_{D,i,G}\right\}$$

corresponding to i-th target vector using the local and global donar vector by (3.3).

Step 2.2. Crossover step

Generate a trial vector,

$$\vec{U}_{i,G} = \left\{\vec{U}_{1,i,G}, \ldots, \vec{U}_{D,i,G}\right\}$$

for the i-th target vector $\vec{x}_{i,G}$ through binomial crossover using (4.1).

Step 2.3. Selection step

Evaluate the trial vector $\vec{U}_{i,G}$

IF $f\left(\vec{U}_{i,G}\right) \leq f\left(\vec{x}_{i,G}\right)$

THEN

$\vec{x}_{i,G+1} = \vec{U}_{i,G}, f\left(\vec{x}_{i,G+1}\right) = f\left(\vec{U}_{i,G}\right)$

END IF

END FOR

Step 2.4. Increase the generation count

G=G+1

END WHILE

6. SIMULATION RESULTS AND DISCUSSION

The effectiveness of hybrid DE-NSO method is verified based on three test systems of economic load dispatch comprising prohibited operating zones, valve point loading and spinning reserve constraints.

The software used is MATLAB 7.8 and executed on a Pentium Dual 2.0GHz personal computer. Hereinafter, the results represent the average of 50 runs of the proposed method for all the five test cases. The following cases are considered for the test systems.

Case study 1. 10 unit with valve point loading prohibited zones and spinning reserve.

Case study 2. 13 unit with valve point loading prohibited zones and spinning reserve.

Case study 3. 10 unit with prohibited zones and spinning reserve

Case study 4. 13 unit with prohibited zones and spinning reserve

Case study 5. 15 unit with prohibited zones and spinning reserve

All the above case studies are simulated for 50 trial runs to few strategies of classical DE and the proposed DE-NSO as shown in table 1, where DES refers to DE strategy.

Table 1.Various strategies of DE

Strategy	Description
DES (1)	DE/current/to/best/1/bin
DES (2)	DE/current/to/best/2/bin
DES (3)	DE_current_to_rand_1_bin
DES (4)	DE_rand_1_bin
DE-NSO	DE with NSO

6.1. Control parameters in DE-NSO

[31] The presented DE-NSO uses six control variables, i.e. population size NP, maximum number of generations NG, neighborhood size k, scaling factor F, crossover rate Cr, and weight factor w. After a number of trials, the control parameters value chosen are: NP = 20, NG = 200, Cr = 0.9 and scale factors 0.8. The size of the neighborhood weight factor and the weight factor is discussed in sections 6.2 and 6.3 respectively. The consistency in getting optimal solution and comparison of solution quality of proposed DE-NSO with other techniques is carried out by taking 50 independent runs.

6.2. Weight factor, w

Four new parameters such as α, β, w, and the neighborhood radius denoted as k are intiated by DE-NSO. Among these parameter, α and β perform the similar role as that of the constant F in classical DE [32]. For the purpose of minimizing the parameters used, assumptions are made such that $\alpha = \beta = F$. In DE-NSO, weight factor w is examined to be the crucial parameter as it stabilizes the exploration and exploitation capability. Choosing a component with w value smaller or even close to 0, results in better exploration in local neighbourhood whereas in global neighbourhood, large value of w or value close to 1 is preferred to promote exploitation. Therefore, by choosing w value in the range [0, 1] especially 0.5, balanced DE-NSO versions can be obtained. But this balanced version is not advantageous related to the problem that occurs usually in the system. In such situation, the weight factor with value 0 or 1, and on-line adaptation of w during algorithm execution offer better performance. Optimal values of weight factor depend mainly on the problem at hand.

In this paper, the selection of weight factor, w is done by initializing w to 0 for all vectors and then increasing it to 1 during algorithm execution. Thus, in the first stages of algorithm's execution, exploration is favoured, where w = 0 corresponds to the local neighborhood model and at final stages exploitation is recommended due to higher values of w. Let G denote the generation number, w_G the weight factor at generation G, and G_{max} the maximum number of generation then the weight factor is expressed in (6.1)

$$w_G = \frac{G}{G_{max}} \tag{6.1}$$

This scheme results in slow transition from exploration to exploitation in the early stages of the algorithm's execution, but exhibits faster transition in the later stages.

6.3. Neighborhood size

A tradeoff between the exploration and exploitation can also be affected by the selection of neighborhood size. If the neighborhood size is nearer to or larger than the population size NP, then attraction of most of the vectors towards the specific point is increased, resulting in loss of explorative power of the algorithm. Again, if a small neighborhood size is considered, then the difference vector in the local mutation model becomes too small and it leads to the risk of losing diversity of the population. In this paper, neighborhood size equal to 10% of population size is assumed for both case study.

The proposed DE-NSO approach is tested with five test cases of EDP based on valve-point effects, spinning reserve and prohibited operating zones. The valve-point loading effects of generating units are simplified by adding a recurring sinusoid component to the quadratic cost function. The software used is MATLAB 7.8 and executed on a Pentium dual 2.0GHz personal computer. The results of the proposed method for all the five test cases represent an average of 50 runs. Table I shows the description of the test system applied for the proposed technique.

6.4. Case study 1

This test case consists of ten generating units that include prohibited operating zones, valve point loading and spinning reserve. The load demand expected to meet all the requirements of ten generating units is 1800MW. The data related to the system generator unit is briefly explained in [33]. The effectiveness of combining NSO with DE is shown by evaluating the problem with other strategies. This proposed method comprises of 50 trial runs and at each trial, an average of five iterations is performed thus a best solution of $115809.063 is recorded. Similarly, a best solution of $99299.79 is recorded by the proposed method for all the 50 trial runs without the constraint of spinning reserve.The final fuel cost obtained using DES (1), DES (2), DES (3), DES (4) and the power demand of 1263 MW for the proposed method with and without spinning reserve constraint are summarized in table A1. Thus the advantage or effectiveness of using this proposed method to produce quality solution is showed by solving the case study under two conditions. From tables A1-A3, it is clear that the minimum cost resulted from this proposed method is relatively less when compared to all other methods.

Figure 1 shows the convergence movement of DE-NSO method for power demand of 1800MW. By visual interpretation, it is seen that change in the solution is very frequent at initial level, but towards the progress of run, the change is relatively small due to the fine tuning of DE by NSO. Thus the superiority of the proposed method is showed in terms of convergence characteristics without any premature convergence problem. The average number of iterations to reach the optimum solution of the DE-NSO is 8-12 in all the 50 trial runs. Different hardware are used to measure the computation time of different methods and hence the computation time of the DE-NSO is not compared with other solution methods.

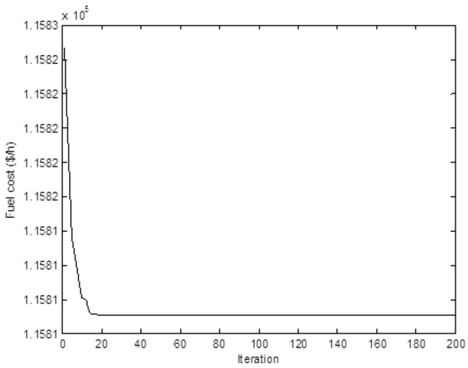

Figure 1.Convergence characteristics of DE-NSO method for 10 unit system (with spinning reserve)

6.5. Case study 2

The results for the case study 2 are tabulated in tables A4-A6 with the results of other strategies of DE. From the comparison results shown in table A4-A6, it is inferred that amongst the three algorithms, DE-NSO, DES (4), DES (1) yields best results with smaller variations among them and DES (2) gives the worst in all accounts. The best cost of each strategy (for both with and without spinning reserve) is tabulated in table A4.

From table A6, it is shown that all the five strategies of DE satisfy the demand, but the allocation of schedule to each unit differs for each method. Among the various schedules, the best allocation schedule is reported by DE-NSO (shown in table A5) producing total final costs of $28407.0779 (with spinning reserve) and $23837.19 (without spinning reserve).

This case study is carried out for a 13 unit system subjected to prohibited operating zones, valve point loading and spinning reserve constraints. Figure 2 shows the convergence characteristics of DE-NSO for 13 unit system with spinning reserve. The system data can be found from [29].

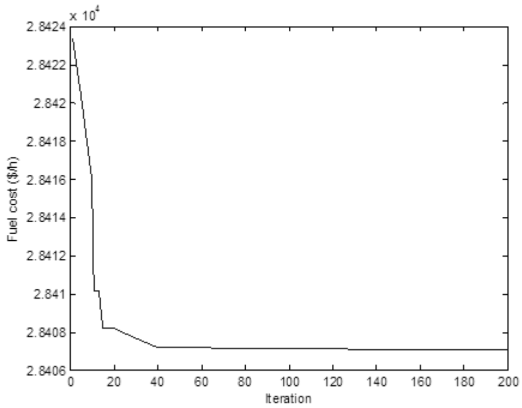

Figure 2.Convergence characteristics of DE-NSO method for 13 unit system (with spinning reserve)

6.6. Case study 3

This case study deals with ten unit system considering only spinning reserve and prohibited operating zones. Main data of the system includes cost coefficients, initial power outputs and prohibited operating zones [34]. Table A7 shows the minimum cost achieved by the DE-NSO method and other DE strategies. The result confirms that the DE-NSO method yields best cost among the tested strategies. The best cost of $116747.227 and $99782.573 for DE-NSO with and without spinning reserve is obtained respectively. Tables A8 and A9 show the generation schedules for each method.

6.7. Case study 4

This case study investigates the applicability of DES (1), DES (2), DES (3), DES (4) and DE_NSO for a 13 unit system. The unit characteristics are obtained from [29]. A summary of test results are presented in tables A10-A12. The best cost of $28617.0638 and $24093.153 are obtained using DE-NSO method as shown in table A10. For this case study, same parameter selection method is employed as the case studies 1, 2 and 3. It is evident from the results that the DE-NSO has shown superiority to the conventional DE strategies.

6.8. Case study 5

In this case, the experiment is performed on a 15 thermal unit system, which considers only prohibited operating zones and spinning reserves. The technical limits, cost coefficients and constraint details are provided in [33]. The comparison results for the best generation schedule and best cost as obtained by DE-NSO method are given in tables A13-A15. The total demand of the system is 2520MW. The table result shows that the DE-NSO is succeeded in finding satisfactory solution for the above test case and it has also shown the superiority to the existing DE strategies. Figure 3 describes the convergence characteristics of DE-NSO for 15 unit system with spinning reserve.

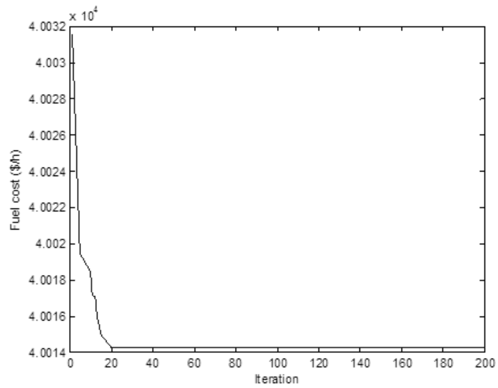

Figure 3.Convergence characteristics of DE-NSO method for 15 unit system (with spinning reserve)

7. CONCLUSION

In this paper, a NSO furnished with linearly increasing weight factor is presented in an attempt to stablize the effects of exploration and exploitation ability of DE. Performance comparison with other optimization techniques indicates that this proposed method enhances the ability of DE to locate the solutions accurately in the search space.This also integrates differential evolution method with NSO, to solve the valve-point effects of ELD problem. Several modifications are made to overcome the pre-mature convergence problem of DE thus dealing with the constraints of complex non-smooth ELD problem. Three test systems are evaluated based on presented DE-NSO method and the dispatch results obtained are directly compared with the other techniques reported in the recent literatures. The simulation results signify the superiority of the proposed method based on convergence properties and computational efficiency.

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APPENDIX

Table A1.Comparison of best results with and without spinning reserve (case study1)

Unit	Fuel cost of each unit including spinning reserve generation				
	DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
1	9996.483	9879.080	9846.594	9977.781	9868.141
2	8611.0086	8855.426	8658.0687	9457.392	9508.499
3	17724.196	17948.626	17948.626	17948.626	17948.626
4	15943.609	15967.575	15967.575	15885.009	15832.667
5	12000.818	11714.930	11714.936	11714.936	11714.936
6	8239.885	7882.266	7882.266	7882.266	7882.266
7	5755.268	6419.409	6419.409	6419.409	6419.409
8	6110.074	5966.759	5966.759	5966.759	5966.759
9	5425.572	5336.188	5336.188	5336.188	5336.188
10	10385.829	9420.426	9640.424	8777.578	8822.294
Cost	116752.694	115910.640	115909.827	115888.428	115809.063
Unit	Fuel cost of unit excluding spinning reserve generation				
	DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
1	8277.249	9124.176	9159.288	9071.881	9125.872
2	8628.929	8530.817	8333.459	9132.783	9183.89
3	16389.36	16872.69	16872.69	16872.69	16872.69
4	14694.46	14123.7	12780.12	14189.59	13712.26
5	10620.45	10098.41	10098.41	10098.41	10098.41
6	4822.745	4614.353	5847.837	4614.353	4888.918
7	4007.897	4963.394	4963.394	4963.394	4963.394
8	4881.614	2685.22	2718.69	2685.22	2685.22
9	2700.533	3900.579	3900.579	3900.579	3900.579
10	8609.555	7957.414	8177.413	7314.567	7359.282
Cost	100192.747	99390.69	99380.85	99365.95	99299.79

Table A2.Dispatch result of DE-NSO different DE strategies of case study 1

Generation		DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
P1	PG	150.2416	150.28129	150	151.5383	150
	SR	2.7074	3.02825	1.30367	6.7982	31.7736
P2	PG	148.5499	140.03387	137.4271	147.8948	135
	SR	-	-	-	-	-
P3	PG	340	340	340	340	340
	SR	-	-	-	-	-
P4	PG	299.505	300	300	299.7399	300
	SR	23.9247	16.9717	50	13.2017	2.8
P5	PG	243	243	243	243	243
	SR	-	-	-	-	-
P6	PG	160	160	160	160	160
	SR	43.3678	50	19.01903	50	50
P7	PG	130	130	130	130	119.458
	SR	-	-	-	-	-
P8	PG	120	120	120	120	120
	SR	50	50	49.6772	50	35.425
P9	PG	80	80	80	80	80
	SR	-	-	-	-	-
P10	PG	128.7034	136.6848	139.5715	127.8267	152.5419
	SR	-	-	-	-	-

Table A3.Generator loading and fuel cost of case study 1 with total load demand of 1800MW

Unit	DES(1)		DES(2)		DES(3)		DES(4)		DE-NSO	
	Power	SR	Power	SR	Power	SR	Power	SR	Power	SR
P1	150.2416	2.7074	150.28129	3.02825	150	1.30367	151.5383	6.7982	150	31.7736
P2	148.5499	-	140.03387	-	137.4271	-	147.8948	-	135	-
P3	340	-	340	-	340	-	340	-	340	-
P4	299.505	23.9247	300	16.9717	300	50	299.7399	13.2017	300	2.8
P5	243	-	243	-	243	-	243	-	243	-
P6	160	43.3678	160	50	160	19.019	160	50	160	50
P7	130	-	130	-	130	-	130	-	119.458	-
P8	120	50	120	50	120	49.6772	120	50	120	35.425
P9	80	-	80	-	80	-	80	-	80	-
P10	128.7034	-	136.6848	-	139.5715	-	127.8267	-	152.54	-
Total	1800	120	1800	120	1800	120	1800	120	1800	120
Cost	116752.694		115910.6409		115909.8274		115888.4289		115809.063	

Table A4.Comparison of best results with and without spinning reserve (case study 2)

Unit	Fuel cost of each unit including spinning reserve generation				
	DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
1	5350.2451	5267.762	5324.0356	5350.2454	5424.8807
2	3186.6425	3111.639	3186.6425	3186.6425	3186.6425
3	3184.6425	3109.639	3184.6425	3184.6425	3184.6425
4	951.3284	1444.150	933.1514	951.3280	933.3611
5	951.3283	1529.126	1529.126	1529.1260	1529.1260
6	1560.2213	1560.221	1560.2213	1560.2213	1560.2213
7	1560.2213	1560.221	1560.2213	1560.2213	1560.2213
8	1529.1260	1529.126	933.1514	951.3281	932.7526
9	1529.1260	895.677	1529.126	1529.1260	1529.1260
10	1156.5904	1156.590	1156.590	1156.5904	1156.5904
11	1156.5904	1156.590	1156.590	1156.5904	1156.59046
12	902.9810	770.9768	802.8832	902.9810	804.80376
13	818.7010	770.9767	990.2985	818.7013	880.2332
Cost	28657.2387	28660.36	28503.354	28473.9417	28407.0779
Unit	Fuel cost of unit excluding spinning reserve generation				
	DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
1	4800.245	4717.762	4774.036	4800.245	4874.881
2	2877.643	2802.639	2877.643	2877.643	2877.643
3	2877.643	2802.639	2877.643	2877.643	2877.643
4	800.716	1293.538	209.6797	227.8563	209.8894
5	253.7308	831.529	1378.514	1378.514	831.5285
6	1329.11	942.683	942.6825	1243.758	1409.609
7	942.6825	942.683	1243.758	1409.609	1409.609
8	1378.514	1345.608	235.5539	253.7306	235.1551
9	805.6543	172.206	805.6543	805.6543	805.6543
10	1052.258	1052.258	1052.258	1052.258	1052.258
11	1052.258	1052.258	1052.258	1052.258	1052.258
12	430.1041	551.3098	776.4567	430.1041	778.3774
13	417.693	557.9207	963.872	792.2748	853.8067
Cost	23837.7446	23862.69	23846.68	23839.74	23837.19

Table A5.Dispatch result of DE-NSO different DE strategies of case study 2

		DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
P1	PG	606.0030	610.5396	604.3309	606.00302	600.55765
	SR	-	-	-	-	-
P2	PG	360	360	360	360	354.9827
	SR	-	-	-	-	-
P3	PG	360	360	360	360	354.9827
	SR	-	-	-	-	-
P4	PG	99.5168	98.3709	98.3573	99.51686	130
	SR	-	50	50	50	-
P5	PG	99.5168	140	140	140	140
	SR	40	40	-	-	40
P6	PG	150	150	150	150	150
	SR	5	-	30	9.9999	30
P7	PG	150	150	150	150	150
	SR	30	-	10	-	30
P8	PG	140	98.33156	98.3573	99.51687	140
	SR	-	40	40	40	2.0979
P9	PG	140	140	140	140	95.8453
	SR	50	50	50	50	50
P10	PG	120	120	120	120	120
	SR	-	-	-	-	-
P11	PG	120	120	120	120	120
	SR	-	-	-	-	-
P12	PG	90	84.07832	83.9542	90	81.8157
	SR	30	-	-	30	14.1491
P13	PG	84.96322	88.67955	95	84.96324	81.8157
	SR	25	-	-	-	13.7529

Table A6.Generator loading and fuel cost of case study 2 with total load demand of 2520 MW

Unit	DES(1)		DES(2)		DES(3)		DES(4)		DE-NSO	
	Power	SR	Power	SR	Power	SR	Power	SR	Power	SR
P1	606.0030	-	610.5396	-	604.3309	-	606.00302	-	600.55765	-
P2	360	-	360	-	360	-	360	-	354.98277	-
P3	360	-	360	-	360	-	360	-	354.98278	-
P4	99.5168	-	98.3709	50	98.3573	50	99.51686	50	130	-
P5	99.5168	40	140	40	140	-	140	-	140	40
P6	150	5	150	-	150	30	150	9.99	150	30
P7	150	30	150	-	150	10	150	-	150	30
P8	140	-	98.33156	40	98.3573	40	99.51687	40	140	2.0979
P9	140	50	140	50	140	50	140	50	95.84534	50
P10	120	-	120	-	120	-	120	-	120	-
P11	120	-	120	-	120	-	120	-	120	-
P12	90	30	84.07832	-	83.9542	-	90	30	81.815718	14.1491
P13	84.96322	25	88.67955	-	95	-	84.96324	-	81.815713	13.7529
Total	2520	180	2520	180	2520	180	2520	180	2520	180
Cost	28657.2387		28660.36		28503.354		28473.9417		28407.0779	

Table A7.Comparison of best results with and without spinning reserve (case study 3)

Unit	Fuel cost of each unit including spinning reserve generation				
	DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
1	9996.483	9996.4838	9996.483	10041.506	9996.4838
2	8611.0086	8611.0086	8611.0086	8865.222	9026.0518
3	18021.608	18021.6077	18021.6077	18021.607	18021.6077
4	15921.181	15921.1811	15921.1811	15921.181	15921.1811
5	11732.159	11732.1589	11732.1589	11732.158	11732.1589
6	7938.1632	7938.1632	7938.1632	7938.163	7938.1632
7	6401.5465	6401.5465	6401.5465	6401.546	6401.5465
8	6010.5125	6010.5125	6010.5125	6010.512	6010.5125
9	5319.6376	5319.6376	5319.6376	5319.637	5319.6376
10	9837.419	9837.4199	9837.419	9536.352	9415.2297
Cost	116754.49	116754.374	116754.3747	116754.0352	116747.227
Unit	Fuel cost of unit excluding spinning reserve generation				
	DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
1	9076.866	9044.836	9044.836	8994.644	9044.837
2	8159.684	8159.684	8159.684	8413.897	8574.727
3	16971.61	16971.61	16971.61	16971.61	16971.61
4	13828.18	13841.84	13841.84	13978.48	13841.84
5	10073.59	10073.59	10073.59	10073.59	10073.59
6	4864.012	4891.026	4891.026	4804.412	4891.026
7	4950.842	4950.842	4950.842	4950.842	4950.842
8	2703.288	2703.288	2703.288	2703.288	2703.288
9	3828.858	3820.332	3820.331	3864.031	3820.331
10	8368.016	8368.017	8368.016	8066.949	7945.827
Cost	99789.7199	99789.7199	99789.719	99787.8886	99782.573

Table A8.Generator loading and fuel cost of case study 3 with total load demand of 1800 MW

Unit	DES(1)		DES(2)		DES(3)		DES(4)		DE-NSO	
	Power	SR	Power	SR	Power	SR	Power	SR	Power	SR
P1	150	4.207	150	4.207	150	4.207	150.533	6.5771	150	3.400
P2	140.511	-	135	-	135	-	138.385	-	135	-
P3	340	-	340	-	340	-	340	-	340	-
P4	300	21.396	300	21.396	300	21.396	300	17.954	300	21.739
P5	243	-	243	-	243	-	243	-	243	-
P6	160	43.295	160	43.2952	160	43.295	160	45.4682	160	43.973
P7	130	-	130	-	130	-	130	-	130	-
P8	120	50	120	50	120	50	120	50	120	50
P9	80	1.100	80	1.100	80	1.100	80	-	80	0.8865
P10	136.488	-	141.999	-	141.999	0	138.080	-	141.999	-
Total	1800	120	1800	120	1800	120	1800	120	1800	120
Cost	116754.49		116754.374		116754.3747		116754.0352		116747.227	

Table A9.Dispatch result of DE-NSO different DE strategies of case study 3

Generation		DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
P1	PG	150	150	150	150.533	150
	SR	4.207	4.207	4.207	6.5771	3.400
P2	PG	140.511	135	135	138.385	135
	SR	-	-	-	-	-
P3	PG	340	340	340	340	340
	SR	-	-	-	-	-
P4	PG	300	300	300	300	300
	SR	21.396	21.396	21.396	17.954	21.739
P5	PG	243	243	243	243	243
	SR	-	-	-	-	-
P6	PG	160	160	160	160	160
	SR	43.295	43.295	43.295	45.4682	43.973
P7	PG	130	130	130	130	130
	SR	-	-	-	-	-
P8	PG	120	120	120	120	120
	SR	50	50	50	50	50
P9	PG	80	80	80	80	80
	SR	1.100	1.100	1.100	-	1.100
P10	PG	136.488	141.999	141.999	138.080	141.999
	SR	-	-	-	-	-

Table A10.Comparison of best results with and without spinning reserve (case study 4)

Unit	Fuel cost of each unit including spinning reserve generation				
	DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
1	6187.472	6187.472	6187.467	6036.783	6021.252
2	3297.576	3297.576	3297.576	3297.576	2519.343
3	3295.576	3295.576	3295.576	3295.576	3295.576
4	1300.956	1300.956	1300.956	1300.956	1300.956
5	1387.104	1387.104	1387.104	1340.58	1387.104
6	1473.9	1473.9	1473.9	1473.9	1473.9
7	1473.9	1473.9	1473.9	1309.184	1374.578
8	1387.104	1387.104	1387.104	1387.104	1387.104
9	1387.104	1387.104	1387.104	1387.104	1114.911
10	474.544	1198.896	720.7941	589.963	1198.896
11	1198.896	474.544	720.275	1098.897	1198.896
12	607.591	607.591	718.583	607.591	923.004
13	607.591	607.591	718.111	968.631	968.631
Cost	28618.1812	28717.5172	28590.0452	28644.5194	28617.0638
Unit	Fuel cost of unit excluding spinning reserve generation				
	DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
1	5637.472	5637.472	5637.467	5486.783	5471.252
2	2988.576	2988.576	2988.576	2988.576	2210.343
3	2988.576	2988.576	2988.576	2988.576	2988.576
4	665.856	825.944	805.296	1060.956	957.818
5	832.32	832.32	886.585	785.796	926.651
6	1005.979	998.784	1048.885	998.784	1026.883
7	1066.18	998.784	1011.915	834.068	919.192
8	1048.655	1147.104	930.876	1147.104	942.181
9	939.408	752.004	879.0451	752.004	692.4997
10	348.544	1072.896	594.7941	463.963	1072.896
11	1072.896	348.544	594.275	972.897	1072.896
12	479.535	481.591	590.096	221.035	709.764
13	481.591	481.591	590.821	842.631	625.856
Cost	24099.314	24095.314	24095.4514	24112.8474	24093.153

Table A11.Dispatch result of DE-NSO different DE strategies of case study 4

		DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
P1	PG	680	680	679.999	662.221	660.387
	SR	-	-	-	-	-
P2	PG	360	360	360	360	267.919
	SR	-	-	-	-	-
P3	PG	360	360	360	360	360
	SR	-	-	-	-	-
P4	PG	130	130	130	130	130
	SR	50	29.9869	32.5875	-	13.2518
P5	PG	140	140	140	134.608	140
	SR	40	40	33.1974	40	28.1505
P6	PG	150	150	150	150	150
	SR	29.0928	30	23.6692	30	26.4535
P7	PG	150	150	150	130.958	138.550
	SR	21.4762	30	28.3439	30	27.5109
P8	PG	140	140	140	140	140
	SR	12.6525	-	27.6172	-	26.1888
P9	PG	140	140	140	140	108.142
	SR	26.539	50	34.1448	50	23.3393
P10	PG	40	120	67.6507	53.0209	120
	SR	-	-	-	-	-
P11	PG	120	40	67.5930	109.190	120
	SR	-	-	-	-	-
P12	PG	55	55	67.4046	55	90
	SR	0.23913	-	0.28923	30	10.1104
P13	PG	55	55	67.3520	95	95
	SR	-	-	0.15000	-	25

Table A12.Generator loading and fuel cost of case study 4 with total load demand of 2520 MW

Unit	DES(1)		DES(2)		DES(3)		DES(4)		DE-NSO	
	Power	SR	Power	SR	Power	SR	Power	SR	Power	SR
P1	680	-	680	-	679.999	-	662.221	-	660.387	-
P2	360	-	360	-	360	-	360	-	267.919	-
P3	360	-	360	-	360	-	360	-	360	-
P4	130	50	130	29.9869	130	32.5875	130	-	130	13.2518
P5	140	40	140	40	140	33.1974	134.608	40	140	28.1505
P6	150	29.0928	150	30	150	23.6692	150	30	150	26.4535
P7	150	21.4762	150	30	150	28.3439	130.958	30	138.550	27.5109
P8	140	12.6525	140	-	140	27.6172	140	-	140	26.1888
P9	140	26.539	140	50	140	34.1448	140	50	108.142	23.3393
P10	40	-	120	-	67.6507	-	53.0209	-	120	-
P11	120	-	40	-	67.5930	-	109.190	-	120	-
P12	55	0.23913	55	-	67.4046	0.28923	55	30	90	10.1104
P13	55	-	55	-	67.3520	0.15000	95	-	95	25
Total	2520	180	2520	180	2520	180	2520	180	2520	180
Cost	28618.1812		28717.5172		28590.0452		28644.5194		28617.0638	

Table A13.Comparison of best results with and without spinning reserve (case study 5)

Unit	Fuel cost of each unit including spinning reserve generation				
	DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
1	4810.543	4810.543	4810.543	4808.455	4810.543
2	5029.105	5252.88557	5252.885	5252.885	5252.885
3	1265.26	1265.26	1265.26	1265.26	1265.26
4	1265.26	1265.26	1265.26	1265.26	1265.26
5	5394.284	4759.460	3400.083	3659.777	4957.272
6	5339.691	5339.691	5339.691	5339.6916	5339.691
7	4677.689	4677.689	4677.689	4677.6899	4677.689
8	900.2168	900.2168	900.2168	900.2168	900.216
9	453.504	453.504	453.504	453.504	453.5043
10	443.251	443.251	1586.330	1586.330	443.2518
11	810.909	810.909	641.245	810.9096	810.909
12	651.328	1057.283	1057.283	1051.566	857.468
13	552.731	552.731	1078.067	552.731	552.731
14	490.934	490.934	490.934	490.934	490.934
15	510.000	510.000	510.000	510.000	510
Cost	40021.3129	40016.223	40195.257	40052.9545	40014.221
Unit	Fuel cost of unit excluding spinning reserve generation				
	DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
1	3633.796	3633.796	3735.065	3650.313	3633.796
2	4455.105	4678.886	4678.885	4678.885	4678.885
3	626.2466	626.2466	626.2466	626.2466	626.2466
4	626.2466	626.2466	626.2466	626.2466	626.2466
5	4933.284	4298.46	2939.083	3198.777	4496.272
6	4709.691	4709.691	4709.691	4709.692	4709.691
7	3638.779	3638.779	3638.779	3638.78	3638.779
8	673.2168	673.2168	112.3718	673.2168	673.216
9	280.504	280.504	280.504	280.504	280.5043
10	53.77	53.77	1411.33	1177.104	53.7708
11	419.4746	419.475	455.245	419.4756	419.475
12	421.328	827.283	827.283	821.566	627.468
13	327.731	327.731	853.067	327.731	327.731
14	181.934	181.934	181.934	181.934	181.934
15	187	187	187	187	187
Cost	32594.713	32589.623	32728.997	32625.214	32587.6214

Table A14.Generator loading and fuel cost of case study 5 with total load demand of 2650 MW

Unit	DES(1)		DES(2)		DES(3)		DES(4)		DE-NSO	
	Power	SR	Power	SR	Power	SR	Power	SR	Power	SR
P1	404.9999	49.999	404.999	50	404.999	49.9999	404.798	48.4461	404.999	40
P2	433.405	-	455	-	455	-	455	-	455	-
P3	100	30	100	30	100	30	100	30	100	30
P4	100	30	100	30	100	30	100	30	100	30
P5	470	-	410.000	-	428.711	-	305.732	-	281.0472	-
P6	460	-	460	-	460	-	460	-	460	-
P7	415	50	415	50	415	50	415	50	415	50
P8	60	-	60	-	60	-	60	7.1125	60	50
P9	25	-	25	-	25	-	25	-	25	-
P10	25	20	25	20	25	30	130	14.4412	130	-
P11	60	20	60	20	60	10	60	20	43.952	-
P12	41.594	-	80	-	61.288	-	79.469	-	80	-
P13	25	-	25	-	25	-	25	-	65	-
P14	15	-	15	-	15	-	15	-	15	-
P15	15	-	15	-	15	-	15	-	15	-
Total	2650	200	2650	200	2650	200	2650	200	2650	200
Cost	40021.3129		40016.223		40195.257		40052.9545		40014.221	

Table A15.Dispatch result of DE-NSO different DE strategies of case study 5

		DES(1)	DES(2)	DES(3)	DES(4)	DE-NSO
P1	PG	404.9999	404.999	404.999	404.798	404.999
	SR	49.999	50	49.9999	48.4461	49.9999
P2	PG	433.405	455	455	455	455
	SR	-	-	-	-	-
P3	PG	100	100	100	100	100
	SR	30	30	30	30	30
P4	PG	100	100	100	100	100
	SR	30	30	30	30	30
P5	PG	470	410.000	428.711	305.732	281.0472
	SR	-	-	-	-	-
P6	PG	460	460	460	460	460
	SR	-	-	-	-	-
P7	PG	415	415	415	415	415
	SR	50	50	50	50	50
P8	PG	60	60	60	60	60
	SR	-	-	-	7.1125	-
P9	PG	25	25	25	25	25
	SR	-	-	-	-	-
P10	PG	25	25	25	130	130
	SR	20	20	30	14.4412	20
P11	PG	60	60	60	20	43.952
	SR	20	20	10	20	20
P12	PG	41.594	80	61.288	79.469	80
	SR	-	-	-	-	-
P13	PG	25	25	25	25	65
	SR	-	-	-	-	-
P14	PG	15	15	15	15	15
	SR	-	-	-	-	-
P15	PG	15	15	15	15	15
	SR	-	-	-	-	-