

Non-Convex Economic Dispatch by Using Optimization Techniques

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ABSTRACT: Electrical power industry restructuring has created highly vibrant and competitive market that altered many aspects of the power industry. In this changed scenario, scarcity of energy resources, increasing power generation cost, environment concern, ever growing demand of electrical energy necessitate optimal economic dispatch. Practical economic dispatch (ED) problems have nonlinear, non-convex type objective function with intense equality and inequality constraints. The conventional optimization methods are not able to solve such problems as due to local optimum solution convergence. This work proposes a novel metaheuristic optimization methodology aimed at solving economic dispatch problem considering valve point loading effects. The differential evolution (DE) may occasionally stop proceeding toward the global optimum even though the population has not converged to a local optimum. This situation is usually referred to as stagnation. DE also suffers from the problem of premature convergence, where the population converges to some local optima of a multimodal objective function, losing its diversity. Shuffled frog leaping algorithm (SFLA) is a newly developed memetic metaheuristic algorithm for combinatorial optimization, which has simple concept, few parameters, high performance, and easy programming. SFLA and its variants have been successfully applied to various fields of power system optimization. The proposed approach is based on a hybrid shuffled differential evolution (SDE) algorithm which combines the benefits of SFLA and DE.

Keywords: Economic Dispatch, Differential Evolution, Shuffled frog leaping algorithm, shuffled differential evolution.

I. INTRODUCTION

Economic load dispatch (ELD) problem is a classical form of optimization problems and has been one of the most important decision-making processes in the operation of electrical power systems. The total system-wide generation cost is generally defined as the objective function of ELD problem. The equality and inequality power system constraints are embedded in ELD formulation, such as power balance and generation limits of each generating unit's output capacity. ELD problem has been thought of as a mathematically complex and highly nonlinear optimization problem, especially in larger systems. For many decades, many algorithms have been presented to solve the optimization problem of ELD. First, conventional deterministic approaches which resort to mathematical gradient information have been developed to obtain the minimum cost of ELD problem. To overcome the limitations of those deterministic algorithms in real-system applications which are basically associated with the simplification of mathematical formulation, a variety of evolutionary frameworks that employ metaheuristic computational intelligence have explored their capabilities to search optimal solution of ELD problem with little abbreviation of original formulation.

Steam (Thermal) Units Characteristic The thermal unit system generally consists of the boiler, the steam turbine and the generator. Fig. showed a typical boiler-turbine-generator unit. The input of the boiler is fuel, and the output is the volume of steam.

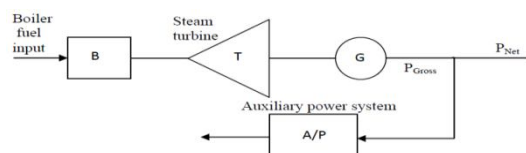


Fig. 1 Boiler-turbine-generator unit

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The electrical output of this set is connected not only to the electric power system, but also to the auxiliary power system in the power plant. For thermal units, we call the input-output characteristic the generating unit fuel consumption function or operating cost function. The unit of the generator fuel consumption function is Btu (British thermal unit) per hour heat input to the unit (or MBtu/hr or Rs/hr or \$/hr). The fuel cost rate times Btu/hr is the \$ per hour (\$/hr) input to the unit for fuel. The output of the generating unit will be designated by P_g the megawatt net power output of the unit.

II. SMOOTH OPERATING COST CURVE OF A THERMAL UNIT

The input-output characteristic of the whole generating unit system can be obtained by combining directly the input-output characteristic of the boiler and the input-output characteristic of the turbine-generator unit. It is a smooth convex curve, which is shown in Fig. 2.2.

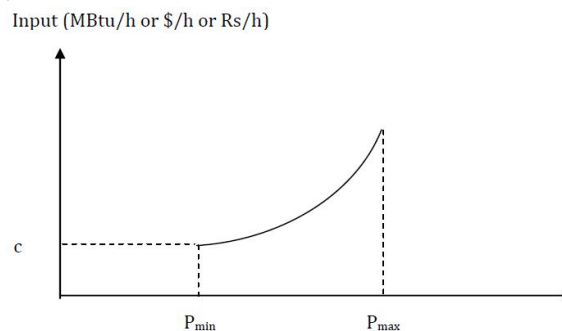


Fig. 2 Input-output Characteristic of generating unit

Generally, the input-output characteristic of generating unit is non-linear. In thermal power plants, fuel cost is an important criterion for economic feasibility. The economic dispatch problem can be formulated by using quadratic or cubic functions of generated power. Let F_G mean the cost, expressed for example in dollars per hour, of producing energy in the generator unit i . The total controllable system production cost such an approach will not be workable for nonlinear functions in practical systems. Therefore will be

$$F = \sum_{i=1}^N F_{G,i}(P_{G,i})$$

The widely used input-output characteristic of the generating unit is a quadratic function i.e.

$$F(P_G) = aP_G^2 + bP_G + c$$

Where a , b , and c are the cost coefficients of the input-output characteristic. The constant c is equivalent to the fuel consumption of the generating unit operation without power output, which is shown in Fig.2.2.

III. ECONOMIC DISPATCH PROBLEM CONSIDERING VALVE-POINT LOADING EFFECT

The generating units with multiple valves in steam turbines are available. The opening and closing of these valves are helpful to maintain the active power balance. However it adds the ripples in the cost function as shown in Fig. which makes the objective function highly nonlinear.

For more rational and precise modelling of fuel cost function, the above expression of cost function is to be modified suitably. The generating units with multi-valve steam turbines exhibit a greater variation in the fuel-cost functions [3]. The valve opening process of multi-valve steam turbines produces a ripple-like effect in the heat rate curve of the generators. These “valve-point effect” are illustrated in Fig.

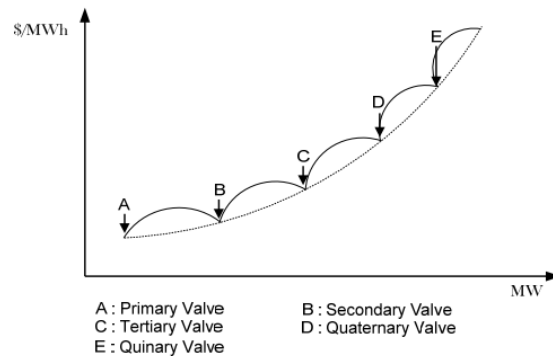


Fig. 3 Valve Point loading effect

The significance of this effect is that the actual cost curve function of a large steam plant is not continuous but more important it is non-linear. The valve-point effects are taken into consideration in the ED problem by superimposing the basic quadratic fuel-cost characteristics with the rectified sinusoidal component as follows:

$$F(P_G) = aP_G^2 + bP_G + c + |e \times \sin(f \times (P_{G,min} - P_G))|$$

where

F is total fuel cost of generation in (\$/hr) including valve point loading.

e, f are fuel cost coefficients of the generating unit reflecting valve-point effects.

IV. PROBLEM DESCRIPTION

The ELD problem can be stated as to determine the optimal set of individual generating units' generation outputs minimizing the objective function(s) as well as satisfying both the equality and inequality constraints. The ELD can, therefore, be mathematically formulated as a continuous variable optimization problem. The objective function to be minimized can be defined as the system-wide generation cost across all the generators. Equality constraint of ELD is a power balancing equation where total power supply of all the generators is equal to the total system demand plus system loss. In addition, individual generators' generation output should be in-between its minimum and maximum generation capacity, and this condition is imposed as the inequality constraint for each generator's output in ELD problem. The mathematical formulation of the generic ELD problem can, therefore, be described as follows:

Minimize $F(P_G) = aP_G^2 + bP_G + c$

Subject to $\sum_{i=1}^N P_{G,i} = P_D$

$P_{min,i} \leq P_i \leq P_{max,i} \quad i = 1, \dots, N$

Moreover, more practical consideration of ELD problem requires an inclusion of valve-point loading effects in ELD problem, and the mathematical formulation of ELD with valve-point loading can be rephrased as follows:

Minimize $F(P_G) = aP_G^2 + bP_G + c + |e \times \sin(f \times (P_{G,min} - P_G))|$

V. SOLUTION METHODS FOR ECONOMIC LOAD DISPATCH

A wide variety of technique has been reported to obtain solution Economic dispatch problem. As it is an optimal problem, broadly optimization techniques are clamped as

1. Conventional method
2. Artificial neural method

1. Conventional method

When making a decision in order to achieve a certain goal, a optimization techniques such as mathematical programming have been utilized in cases where the largest problem can be expressed as a power economical dispatch (PED). On the other hand, if the target problem cannot be expressed in a mathematical equation, neural network, fuzzy logic, expert systems and other decision-making techniques have been utilized. The problem with conventional technique is the difficulty in guaranteeing the generation of good quality solutions



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for cases that have not been verified. It has also a slow convergence of optimization procedure. Some conventional methods are:

i. Lagrangian method The method of Lagrange multipliers can also accommodate multiple constraints. To see how this is done, we need to reexamine the problem in a slightly different manner because the concept of “crossing” discussed above becomes rapidly unclear when we consider the types of constraints that are created when we have more than one constraint acting together.

ii. Gauss seidal method

The Gauss–Seidel method, also known as the Liebmann method or the method of displacement, is an iterative method used to solve a linear system of equations. It is named after the German mathematicians Carl Friedrich Gauss and Philipp Ludwig von Seidel, and is similar to the Jacobi method. Though it can be applied to any matrix with non-zero elements on the diagonals, convergence is only guaranteed if the matrix is either diagonally dominant, or symmetric and positive definite.

iii. Gradient method

The gradient method is an algorithm for the numerical solution of particular systems of linear equations, namely those whose matrix is symmetric and positive-definite. The conjugate gradient method is an iterative method, so it can be applied to sparse systems that are too large to be handled by direct methods such as the Cholesky decomposition. Such systems often arise when numerically solving partial differential equations.

iv. Newton Raphson method

Newton method is a method for finding successively better approximations to the roots (or zeroes) of a real-valued function. The idea of the method is as follows: one starts with an initial guess which is reasonably close to the true root, then the function is approximated by its tangent line (which can be computed using the tools of calculus), and one computes the x-intercept of this tangent line (which is easily done with elementary algebra). This x-intercept will typically be a better approximation to the function's root than the original guess, and the method can be iterated.

1 Artificial neural method

Artificial method has an advantage in that a good quality solution can be obtained even in cases when the target problem cannot be expressed as an equation. Rather than optimization within a small range, as is often said, end users require “total optimization” over a broad range. In comparing with convergence time, it is able to do it in lesser time than conventional methods. Some artificial neural methods are:

i. Genetic Algorithm (GA):

A global optimization technique known as genetic algorithm (GA) has emerged as a candidate due to its flexibility and efficiency for many optimization applications. Genetic algorithm is a stochastic searching algorithm. It combines an artificial, i.e. the Darwinian survival of the fittest, principle with genetic operation, abstracted from nature to form a robust mechanism that is very effective at finding

ii. Evolutionary programming (EP)

Evolutionary computing is an adaptive search technique based on the principles of genetics and natural selection. Evolutionary programming is a probabilistic, global technique. It starts with a population of randomly generated candidate solutions and evolves towards better solutions over a number of generations or iterations. The main stages of this technique include initialization, mutation, competition and selection.

iv. Adaptive neural network (ANN)

Adaptive control theory has evolved as a powerful methodology for designing nonlinear feedback controllers for systems with parametric uncertainty. The fundamental issues of adaptive control for linear systems—selection of controller structures, assumptions of a priori system knowledge, parameterization of adaptive systems, establishment of error models, development of adaptive laws, persistency of excitation, and analysis of closed-loop stability have been extensively addressed.



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V. DIFFERENTIAL EVOLUTION (DE)

Differential evolutionary Programming is a population-based stochastic function minimizes (or maximize) relating to evolutionary computation, whose simple yet powerful and straightforward features make it very attractive for numerical optimization. Differential evolution uses a rather greedy and less stochastic approach to problem solving than do evolutionary algorithms. Differential evolution combines simple arithmetic operators with the classical operators of recombination, mutation and selection to evolve from a randomly generated starting population to a final solution.

Equality Constraints for Active Power Balance

The total power generated should be the same as the total load demand plus the total transmission losses. In this work, transmission power losses have not been considered and the active power balance can be expressed as:

$$\sum_{i=1}^N P_{G,i} = P_D$$

Where, P_D is the total power demand in MW.

Inequality Constraints for Generation Capacity

It is not always necessary that all the units of a plant are available to share a load. Some of the units may be taken off due to scheduled maintenance. Also it is not necessary that the less efficient units are switched off during off peak hours. There is a certain amount of shut down and start up costs associated with shutting down a unit during the off peak hours and servicing it back on-line during the peak hours. To complicate the problem further, it may take about eight hours or more to restore the boiler of a unit and synchronizing the unit with the bus. To meet the sudden change in the power demand, it may therefore be necessary to keep more units than it necessary to meet the load demand during that time. This safety margin in generation is called *spinning reserve*. The optimal load dispatch problem must then incorporate this startup and shut down cost for without endangering the system security.

The power generation limit of each unit is then given by the inequality constraints

$$P_{min,i} \leq P_i \leq P_{max,i} \quad i = 1, \dots, N$$

The maximum limit P_{max} is the upper limit of power generation capacity of each unit. On the other hand, the lower limit P_{min} pertains to the thermal consideration of operating a boiler in a thermal or nuclear generating station. An operational unit must produce a minimum amount of power such that the boiler thermal components are stabilized at the minimum design operating temperature.

VI. CASE STUDIES AND ANALYSIS

Table 1 Comparisons of simulation results of different methods for 3-unit case studysystem

Unit	GA [3]	MPSO [12]	SDE
1	300.00	300.27	300.2669
2	400.00	400.00	400.0000
3	150.00	149.74	149.7331
Total power in MW	850.00	850.00	850.0000
Total cost in \$/h	8234.60	8234.07	8234.0717

In the Table 1, SDE method is also compared with the GA [3] and MPSO [12] methods. The minimum cost for GA [3] and MPSO [12] is 8234.60 \$/h and 8234.07 \$/h respectively Fig. 5.2 shows the distribution of total costs of the SDE algorithm for a load demand of 850 MW for 100 different trials for 3-unit case study and observed that the maximum, minimum and average values are 8250.2047 \$/h, 8234.0717 \$/h and 8240.9518 \$/h respectively. The mean values also highlighted with red line in the fig. 4.

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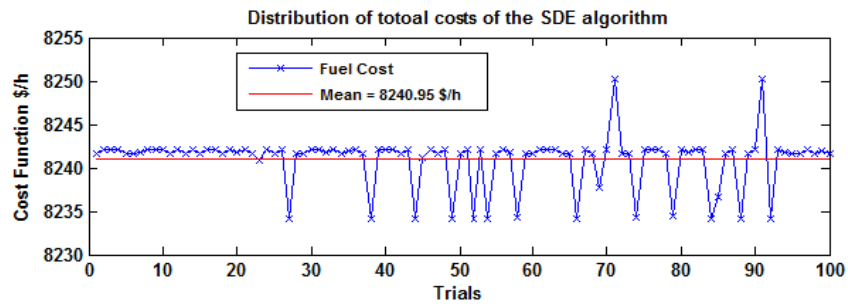


Fig. 4 Distribution of total costs of the SDE algorithm for a load demand of 850 MW for 100 different trials for 3-unit case study

Thirteen unit case study system

The proposed hybrid algorithm is applied on 13-unit system with the effects of valve-point loading.

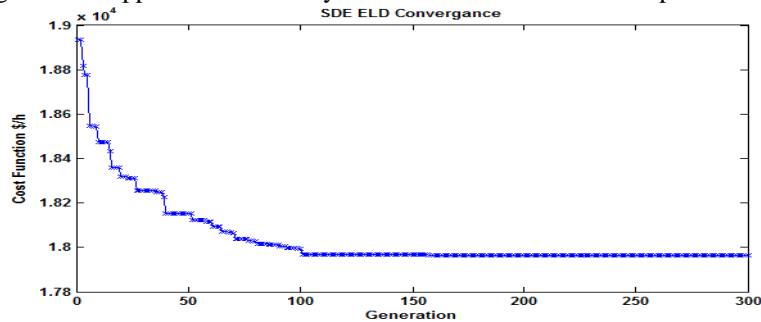


Fig. 5 Convergence profile of the total cost for 13 generating units with $P_D = 1800\text{MW}$

The problem is solved for two different power demands in order to show the effectiveness of the proposed method in producing quality solutions. In the first case, the expected load demand to be met by all the thirteen generating units is 1800 MW. The load demand is set at 2520 MW in second case. The data of the test system have been obtained.

Table 2 Comparisons of simulation results of different methods for 13-unit case study system with $P_D = 1800\text{ MW}$

Unit	IGA_MU [41]	HQPSO [42]	SDE
1	628.3151	628.3180	628.3185
2	148.1027	149.1094	222.7493
3	224.2713	223.3236	149.5995
4	109.8617	109.8650	60.0000
5	109.8637	109.8618	109.8665
6	109.8643	109.8656	109.8665
7	109.8550	109.7912	109.8665
8	109.8662	60.0000	109.8665
9	60.0000	109.8664	109.8665
10	40.0000	40.0000	40.0000
11	40.0000	40.0000	40.0000
12	55.0000	55.0000	55.0000
13	55.0000	55.0000	55.0000
Total power in MW	1800.0000	1800.0000	1800.0000
Total cost in \$/h	17963.9848	17963.9571	17963.8293

Table 2 shows the best dispatch solutions obtained by the proposed method for the load demand of 1800 MW. The convergence profile for SDE method is presented in Fig. 5. The results obtained by the proposed methods are compared with those available in the literature as given in Table 5.2. Though the obtained best solution is not guaranteed to be the

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global solution, the SDE has shown the superiority to the existing methods. The minimum cost obtained by SDE method is 17963.8293 \$/h, which is the best cost found so far and also compared the SDE method with the IGA_MU [41] and HQPSO [42] methods. The minimum cost for IGA_MU [41] and HQPSO [42] is 17963.9848 \$/h and 17963.9571 \$/h respectively. The results demonstrate that the proposed algorithm outperforms the other methods in terms of better optimal solution. Fig. 6 shows the variations of the fuel cost obtained by SDE for 100 different runs and convergence results for the algorithms are presented in Table 5.3 for 1800MW load.

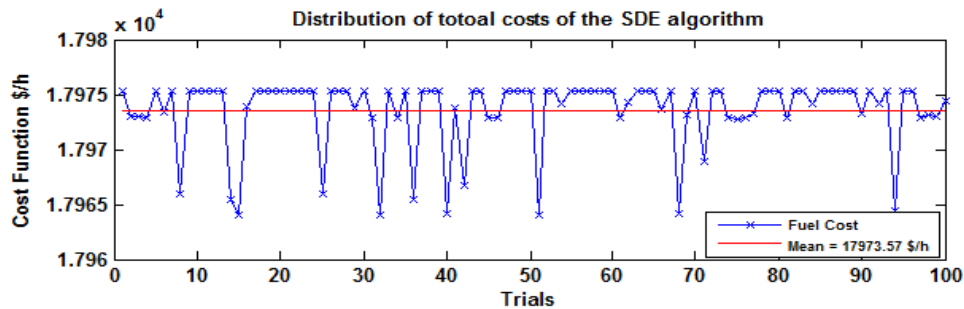


Fig. 6 Distribution of total costs of the SDE algorithm for a load demand of 1800 MW for 100 different trials for 13-unit case study

Fig. 7 shows the variations of the fuel cost obtained by SDE for 100 different runs and convergence results for the algorithms are presented in Table 5.3 for 1800MW load.

Table 3 Convergence results (100 trial runs) for 13-unit test system with $P_D = 1800\text{MW}$

Method	Minimum cost (\$/h)	Average cost (\$/h)	Maximum cost (\$/h)
IGA_MU [41]	17963.9848	NA	NA
HQPSO [42]	17963.9571	18273.8610	18633.0435
SDE	17963.8293	17972.8774	17975.3434

Table 3 shows the convergence results for 100 trials for 13-unit test system with load 1800 MW and compared the minimum, average and maximum cost for IGA_MU [41] and HQPSO [42] methods. It has been observed that minimum, average and maximum costs for SDE proposed method is 17963.8293 \$/h, 17972.8774 \$/h and 17975.3434 \$/h respectively and also observed that the proposed method minimum, average and maximum cost values are low compared with the IGA_MU [41] and HQPSO [42] methods.

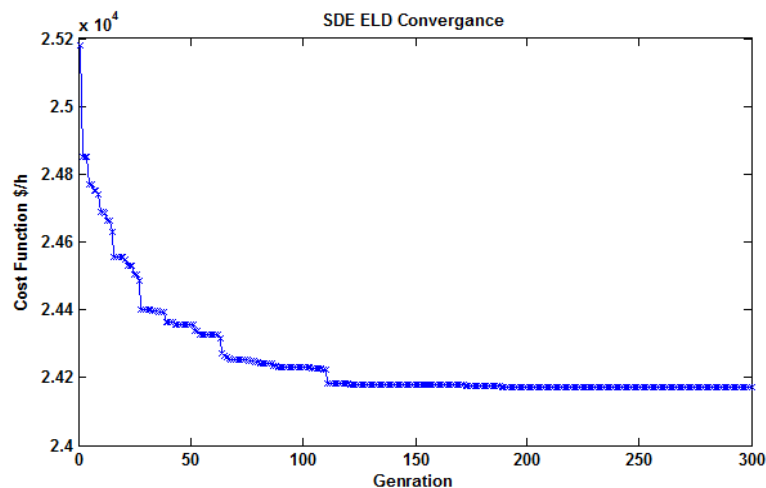


Fig. 7 Convergence profile of the total cost for 13 generating units with $P_D = 2520\text{MW}$

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Table 4 shows the best dispatch solutions obtained by the proposed method for the load demand of 2520 MW. The convergence profile for SDE method is presented in Fig. 7. The results obtained by the proposed methods are compared with those available in the literature as given in Table 4. Though the obtained best solution is not guaranteed to be the global solution, the SDE has shown the superiority to the existing methods. The minimum cost obtained by SDE method is 24169.9177\$/h, which is the best cost found so far and also compared the SDE method with the GA_MU [48] and FAPSO-NM [20] methods. The minimum cost for GA_MU [48] and FAPSO-NM [20] is 24170.7550 \$/h and 24169.92 \$/h respectively.

Table 4 Comparisons of simulation results of different methods for 13-unit case study system with $P_D = 2520$ MW

Unit	GA_MU [48]	FAPSO-NM [20]	SDE
1	628.3179	628.32	628.3185
2	299.1198	299.20	299.1993
3	299.1746	299.98	299.1993
4	159.7269	159.73	159.7331
5	159.7269	159.73	159.7331
6	159.7269	159.73	159.7331
7	159.7302	159.73	159.7331
8	159.7320	159.73	159.7331
9	159.7287	159.73	159.7331
10	159.7073	77.40	77.3999
11	73.2978	77.40	77.3999
12	77.2327	87.69	92.3999
13	92.2598	92.40	87.6845
Total power in MW	2520.0000	2520.0000	2520.0000
Total cost in \$/h	24170.7550	24169.92	24169.9177

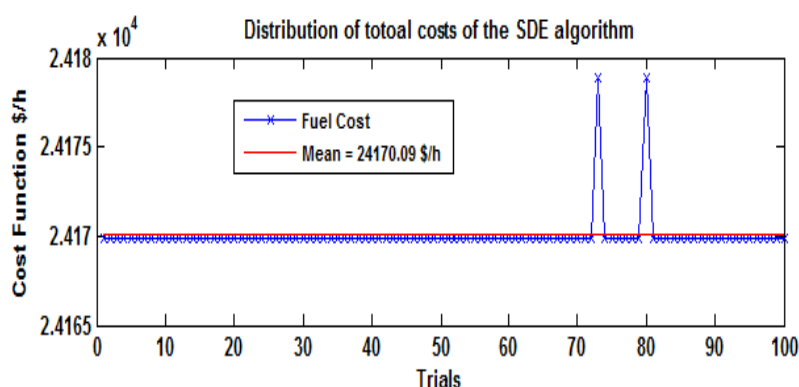


Fig. 8 Distribution of total costs of the SDE algorithm for a load demand of 2520 MW for 100 different trials for 13-unit case study

The results demonstrate that the proposed algorithm outperforms the other methods in terms of better optimal solution. Fig. 8 shows the variations of the fuel cost obtained by SDE for 100 different runs and convergence results for the algorithms are presented in Table 5 for 2520 MW load.

Table 5 Convergence results (100 trial runs) for 13-unit test system with $P_D = 2520$ MW

Method	Minimum cost (\$/h)	Average cost (\$/h)	Maximum cost (\$/h)
GA_MU [48]	24170.7550	24429.1202	24759.3120
FAPSO-NM [20]	24169.9200	24170.0017	24170.4402
SDE	24169.9176	24170.0960	24178.8346

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Forty unit case study system

The ED problem has been solved for a 40 thermal unit’s power system considering the effects of valve-point loading effects. The load demand is 10500 MW. The system data can be found in [7] and given in Table A3.

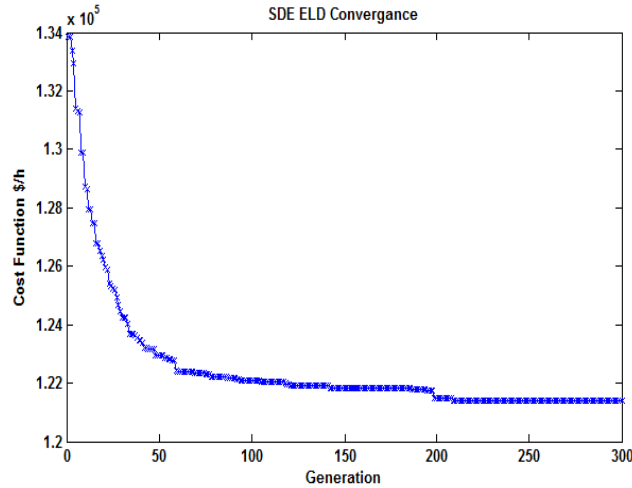


Fig. 9 Convergence profile of the total cost for 40 generating units with $P_D = 10500$ MW

Table 6 Simulation results for 40-unit case study system with $P_D = 10500$ MW

Unit	SDE	Unit	SDE
1	110.7889	21	523.2794
2	110.7998	22	523.2794
3	97.3999	23	523.2794
4	279.7331	24	523.2794
5	87.7999	25	523.2794
6	140.0000	26	523.2794
7	259.5996	27	10.0000
8	284.5996	28	10.0000
9	284.5996	29	10.0000
10	130.0000	30	87.7999
11	94.0000	31	190.0000
12	94.0000	32	190.0000
13	214.7598	33	190.0000
14	394.2794	34	164.7998
15	394.2794	35	200.0000
16	394.2794	36	194.3978
17	489.2794	37	110.0000
18	489.2794	38	110.0000
19	511.2794	39	110.0000
20	511.2794	40	511.2794
Total power in MW			10500.0000
Total cost in \$/h			121412.5355

Table 6 shows the convergence results for 100 trials for 13-unit test system with load 1800 MW and compared the minimum, average and maximum cost for BBO [16] and ACO methods. It has been observed that minimum, average and maximum costs for SDE proposed method is 121412.5355\$/h, 121474.0032\$/h and 121521.0211\$/h respectively.

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Table 7 Convergence results (100 trial runs) for 40-unit test system with $P_D = 10500$ MW

Method	Minimum cost (\$/h)	Average cost (\$/h)	Maximum cost (\$/h)
BBO [16]	121426.9530	121508.0325	121688.6634
ACO [50]	121811.3700	121930.5800	122048.0660
SDE	121412.5355	121474.0032	121521.0211

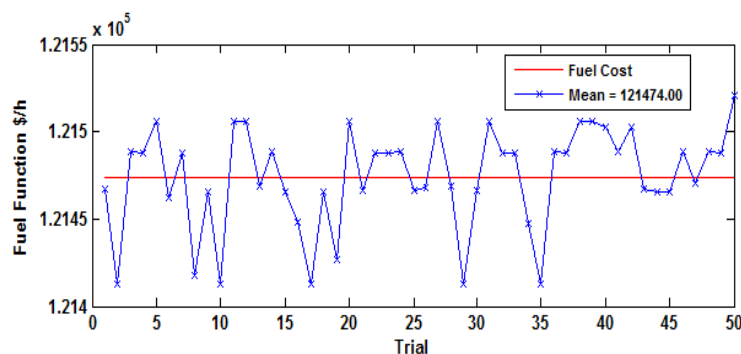


Fig. 10 Distribution of total costs of the SDE algorithm for a load demand of 10500 MW for 100 different trials for 40-unit case study

VII. CONCLUSION

Economic Load Dispatch is one of the fundamental issues in power system operation. The problem of economic load dispatch with equality and inequality constraints has been investigated in this thesis. A novel hybrid heuristic method has been considered with simple active power balance, generation unit limits and valve point loading and successfully applied for non-convex economic dispatch problems solution. The proposed approach is based on a hybrid shuffled differential evolution (SDE) algorithm which combines the benefits of shuffled frog leaping algorithm and differential evolution. The SDE algorithm integrates a novel differential mutation operator specifically designed for effectively addressed the problem. In order to validate the proposed methodology, detailed simulation results obtained on three standard test systems having 3, 13, and 40-units have been presented and discussed. The simulation results showed as the proposed method succeeded in achieving the goal of reduction generation costs. A comparative analysis with other settled nature-inspired solution algorithms demonstrated the superior performance of the proposed methodology in terms of both solution accuracy and convergence performances. Also it has better results compared to the other existing optimization techniques in terms of generation cost and constraints satisfactions and computation time. Therefore, the proposed method can greatly enhance the searching ability; ensure quality of average solutions, and also efficiently manages the system constraints.

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