Economic Load Dispatch Using Strength Pareto Gravitational Search Algorithm with Valve Point Effect

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Abstract— The Strength Pareto Gravitational Search Algorithm (SPGSA) to solve Economic Load Dispatch (ELD) is presents this paper with various generator constraints in power systems. The ELD problem in a power system is to determine the optimal combination of power outputs for all generating units which will minimize the total fuel cost while satisfying all practical constraints. For practical generator operation, many nonlinear constraints of the generator, such as ramp rate limits, prohibited operating zone, generation limits, transmission line loss and non-smooth cost functions are all considered using the proposed technique. The proposed algorithm applied on different test standard power system. The effectiveness of the proposed method is compared with other heuristic algorithm. Results showed the efficiency of the proposed algorithm.

Keywords: SPGSA, Economic Load Dispatch, Valve Point.

I. INTRODUCTION

The efficient and optimum economic operation of electric power systems has always occupied an important position in electric power industry. In recent decades, it is becoming very important for utilities to run their power systems with minimum cost while satisfying their customer demand all the time and trying to make profit. With limited availability of generating units and the large increase in power demand, fuel cost and supply limitation, the committed units should serve the expected load demand with the changes in fuel cost and the uncertainties in the load demand forecast in all the different time intervals in an optimal manner.

The basic objective of ELD of electric power generation is to schedule the committed generating unit outputs, so as to meet the load demand at minimum operating cost while satisfying all unit and system equality and inequality constraints [1]. The ELD problem has been tackled by many researchers in the past [2]. ELD problem involves different problems. The first is Unit Commitment or pre-dispatch problem where in it is required to select optimally out of the available generating sources to operate to meet the expected load and provide a specified margin of operating reserve over a specified period of time. The second aspect of ELD is on-line economic dispatch where in it is required to distribute the load among the generating units actually parallel with the system in such a manner as to minimize the total cost of supplying power. In case of ELD, The generations are not fixed but they are allowed to take values again within certain limits so as to meet a particular load demand with minimum fuel consumption.

The ELD problem is inherently a large-scale, nonlinear, non-convex, non continuous optimization problem. Many techniques are applied to deal with ELD problem both conventional optimization approaches [3-4] such as Linear Programming (LP) or Quadratic Programming (QP) and Artificial Intelligence (AI)-based optimization techniques such as Simulated Annealing (SA) [5], Tabu Search (TS) [6], Genetic Algorithm (GA) [7-8], hybrid TS/SA [9], Evolutionary Programming (EP) [9], and Improved Evolutionary Programming (IEP) [11] etc. Gravitational Search Algorithm (GSA), a new optimization algorithm is applied to solve the above problem. Algorithm, as mentioned earlier is a new search algorithm that has been proven efficient in solving many problems. In the case of ELD, the main use of GSA would be to obtain a solution close to the global optimum in a short period of time.

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II. ELD PROBLEM

The problem of ELD has been introduced in 1960s as an extension of conventional economic dispatch to determine the optimal set of control variables while subject to various equality and inequality constraints. In conventional power flow the values of control variables are pre-specified unlike an ELD value of some control variables need to be found to optimize an objective function [2]. Hence, the ELD is one of the most important optimization strategies for power system managing and nonlinear programming problem. The ELD planning performs the optimal generation dispatch among the operating units to satisfy different constraints that change from problem to problem [12, 14]. In this paper, the ramp rate limits and prohibited operating zone are considered as practical operation constraints of generators for 6 and 15 unit systems and valve-point loading effects without transmission loss is tested to 40 unit system.

Actually, the adjustments of the power output are instantaneous that is one of the unpractical assumptions. Accordingly, generators are constrained because of ramp rate limits where, generation may increase or decrease with corresponding upper and downward ramp rate limits [12]. Therefore, the operating range of all online units is restricted by their ramp rate limits which are defined as:

- Power generation increasing
  \[ P_i^0 - P_i^0 \leq UR_i \]

- Power generation decreasing
  \[ P_i^0 - P_i \leq DR_i \]

Where,
- \( P_i \): The current is output power of \( i \)th unit
- \( P_i^0 \): previous output power
- \( UR_i \): The up ramp limit of the \( i \)th generator
- \( DR_i \): The down ramp limit of the \( i \)th generator

According to this fact that, the prohibited operating zones in the input/output curve of generator are due to vibration in a shaft bearing/steam valve operation it should be noted that, finding the actual prohibited zone by actual performance testing/operating records is really difficult. That leads to getting the best economy by avoiding operation in areas [12]. Therefore, adjustment of the generation output of a unit must avoid operation in the prohibited zones. For this purpose, the feasible operating zones of generators are described as:

\[
A_{ar} = \begin{cases} 
  P_i^{min} \leq P_i \leq P_i^{max} \\
  P_i^{ar,j} \leq P_i \leq P_i^{ar,j+1}, j = 2,3,...,n, i = l,...,m \\
  P_i^{ar,n} \leq P_i \leq P_i^{max} 
\end{cases}
\]

Where, \( A_{ar} = \) Feasible operating zones of \( i \)th unit

Due to minimizing fuel cost is the primary concern of operation planning; the objective of ELD problem in this study is to minimizing total generator fuel cost. That can be expressed as:

\[
F_i = \sum_{i=1}^{m} F_i(P_i) \quad (2)
\]

Where, \( F_i(P_i) = \sum_{i=1}^{m} (a_i P_i^2 + b_i P_i + c_i) \) \( i = 1, ..., m \)

For the mentioned equation, the \( F_i \) is the total generation cost and \( F_i \) is the cost function of the \( i \)th generator. \( a_i, b_i \) and \( c_i \) present the cost coefficients in \( i \)th generator. Also the electrical output of the \( i \)th generator is shown by \( P_i \) and \( m \) is the number of generators committed to the operating system. This constrained ELD problem is subjected to a variety of constraints depending upon assumptions and practical implications [12, 14]. These constraints are discussed as follows. Constrained conditions are:

A. Power Balance

This constraint is based on the principle of equilibrium between total system generation \(( \sum_{i=1}^{m} P_i \) \) and total system loads \(( P_D \) and losses \(( P_L \) \) that is:

\[
\sum_{i=1}^{m} P_i = P_D + P_L, i = 1,...,m \quad (3)
\]

\( P_L \): Obtained using B-coefficients, given by:

\[
P_L = \sum_{i=1}^{m} \sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{m} B_{ii} P_i^0 + B_{00} \quad (4)
\]

B. Generator Operation Constraints

\[
P_i^{min} \leq P_i \leq P_i^{max} \max(P_i^{max} - UR_i, P_i^0 - DR_i) \leq P_i \leq \min(P_i^{max}, P_i^{max} + UR_i) \quad (5)
\]

Where, \( P_i^{min} \) and \( P_i^{max} \) are lower and upper bounds for power outputs of the \( i \)th generating unit.

C. Line Flow Constraints

\[
|P_{lf,k}| \leq P_{lf,k}^{max}, k = l,...,L \quad (6)
\]

Where, \( P_{lf,k} \) is the real power flow of line \( k \); \( P_{lf,k}^{max} \) is the power flow up limit of line \( k \) and \( L \) is the number of transmission lines.

III. GRAVITATIONAL SEARCH ALGORITHM

A. GSA Review

The Gravitational Search Algorithm (GSA) is constructed based on the law of gravity and the notion of mass interactions. GSA is one of the newest heuristic algorithms which have been inspired by the Newtonian laws of gravity and motion. In GSA a set of agents called masses are introduced to find the optimum solution by simulation of Newtonian laws of gravity and motion [15].
Also, each mass agent has four specifications: position, inertia mass, active gravitational mass, and passive gravitational mass. The position of the mass corresponds to a solution of the problem, and its gravitational and inertial masses are determined using a fitness function. In other words, each mass presents a solution, and the algorithm is navigated by properly adjusting the gravitational and inertia masses. By lapse of time, we expect that masses be attracted by the heaviest mass. This mass will present an optimum solution in the search space [16].

The GSA could be considered as an isolated system of masses. It is like a small artificial world of masses obeying the Newtonian laws of gravitation and motion. More precisely, masses obey the following laws:

- **Law of gravity**: Each particle attracts every other particle and the gravitational force between two particles is directly proportional to the product of their masses and inversely proportional to the distance between them, R.
- **Law of motion**: The current velocity of any mass is equal to the sum of the fraction of its previous velocity and the variation in the velocity. Variation in the velocity or acceleration of any mass is equal to the sum of the fraction of its previous velocity and the variation in the velocity. Variation in the velocity or acceleration of any mass is equal to the sum of the fraction of its previous velocity and the variation in the velocity.

To describe the GSA consider a system with s masses in which position of the i^th mass is defined as:

\[
X_i = (x_{i1}, x_{i2}, ..., x_{id}), i = 1, 2, ..., s
\]

Where, \(x_{id}\) is position of the \(i^{th}\) mass in the \(d^{th}\) dimension and \(n\) is the dimension of the search space. According to [19] mass of each agent is computed after calculating current population’s fitness as:

\[
M_i(t) = \frac{q_i(t)}{\sum_{j=1}^{s} q_j(t)}
\]

Where, \(M_i(t)\) is the mass value of the agent \(i\) at \(t\).

\[
q_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)}
\]

Where, \(fit_i(t)\) is the fitness value of the agent \(i\) at \(t\), and worst \((t)\) and best \((t)\) are defined as follows for the minimization problem:

\[
best(t) = \min_{j=1,...,s} fit_j(t) \quad \text{worst}(t) = \max_{j=1,...,s} fit_j(t)
\]

To compute acceleration of an agent, total forces from a set of heavier masses that apply on it should be considered based on the law of gravity, which is followed by calculation of agent acceleration using the law of motion. Afterwards, next velocity of an agent is calculated as a fraction of its current velocity added to its acceleration. Then, its next position can be calculated using:

\[
F_i^d(t) = \sum_{j=best_j} rand_j(t) G(t) \frac{M_j(t)M_i(t)}{R_{ij}(t) + \epsilon} (x^d_j(t) - x^d_i(t))
\]

\[
a_i^d(t) = F_i^d(t) = \sum_{j=best_j} rand_j(t) G(t) \frac{M_j(t)}{R_{ij}(t) + \epsilon} (x^d_j(t) - x^d_i(t))
\]

\[
V_i^d(t + 1) = rand_i \times v_i^d(t) + a_i^d(t)
\]

\[
x_i^d(t + 1) = x_i^d(t) + v_i^d(t + 1)
\]

Where, \(rand_i\) and \(rand_j\) are two uniformly distributed random numbers in the interval \([0, 1]\), \(\epsilon\) is a small value, \(R_{ij}(t)\) is the Euclidean distance between two agents \(i\) and \(j\), defined as \(R_{ij}(t) = \|X_i(t), X_j(t)\|_2\), \(k_{best}\) is the set of first \(K\) agents with the best fitness value and biggest mass, which is a function of time, initialized to \(K_0\) at the beginning and decreasing with time. Here \(K_0\) is set to \(s\) (total number of agents) and is decreased linearly to 1.

In GSA, the gravitational constant, \(G\), will take an initial value, \(G_0\), and it will be reduced with time:

\[
G(t) = G(G_0, t)
\]

Also some differences and advantages of this technique are consisting of [16]:

- In GSA, the agent direction is calculated based on the overall force obtained by all other agents.
- In GSA the force is proportional to fitness value and so agents see the search space around themselves in the influence of force.
- GSA is memory-less and only current position of the agents plays a role in the updating procedure.
- In GSA the force is inversely proportional to the distance between solutions.

Fig. 1 shows the flowchart of the proposed intelligent algorithm.

**B. SPGSA**

If we plot the objective values \(f_1\) and \(f_2\) of these optimal solutions against each other in one plot. A multi-objective optimization algorithm tries to approximate
these solutions but uses a different approach to obtain these solutions. The supposed algorithm sorts the population based on non-dominated fronts. The first front found is ranked the highest and the last one the lowest. This ranking is used in the mating flight selection process. In addition to, for assure diversity in a population (honey bee) employed crowding distance measure.

$$\text{mismatch power} = \sum_{i=1}^{N} P_i \left( G_i \right) - P_d$$

where, \(P_i\) is the power output and \(P_d\) is the total power demand.

IV. SIMULATION AND RESULTS

The different methods discussed earlier are applied to two cases to find out the minimum cost for any demand. In this part the three test systems as: IEEE 6-generator 30-bus, IEEE 14-generator 118-bus IEEE with transmission loss, 15 unit system with prohibited operating zones and ramp rate limits and 40 unit system is tested with valve-point loading effects without transmission loss.

A. Case I. IEEE 30-bus system

In the first case study, the IEEE 30-bus system with six generators and forty one lines is used. The system configuration of the proposed case study is shown in Fig. 3 and the system data can be found in [6,15].

The values of the fuel and emission coefficients of the IEEE 30-bus system are illustrated in Table 1. The line data and bus data of the system are referenced in [1]. The load of the IEEE 30-bus system was set to 2.834 pu on a 100MVA base. In order to demonstrate the effectiveness of the proposed approach on the IEEE 6-generator 30-bus test system. All constraints about emission, fuel cost and system loss are considered. For show efficiency and ability of supposed algorithm in EED problem, used index mismatch power as follows:

$$\text{mismatch power} = \sum_{i=1}^{N} P_i \left( G_i \right) - P_d$$

Where, \(P_i\) is the power output and \(P_d\) is the total power demand.

Results of proposed SPGSA algorithm are compared with the MOPSO [17] and MODE [14], which have been implemented and applied to the EED problem with impressive success. The results of simulation are given in Table 2. The distribution of the non-dominated solutions in Pareto optimal front using the proposed SPGSA is
represented in Fig. 4, which clearly shows the relationships among fuel cost, emission, and transmission loss.

![Figure 4. Three-dimensional Pareto front of SPGSA algorithm for IEEE 30-bus system](image)

<p>| Table I. Generator and emission coefficients of the IEEE 30-bus system. |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|</p>
<table>
<thead>
<tr>
<th>Case</th>
<th>P (MW)</th>
<th>a</th>
<th>c</th>
<th>b</th>
<th>NO</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>G4</th>
</tr>
</thead>
</table>
| 1     | 5      | 2.587 | 6.490 | 5.543 | 4.091 | 100 | 200 | 10 | P
| 2     | 5      | 3.333 | 5.004 | 6.538 | 6.047 | 2.543 | 120 | 150 | 10 | P
| 3     | 5      | 8.000 | 1.064 | 4.586 | 5.094 | 4.258 | 50 | 180 | 20 | P
| 4     | 5      | 8.000 | 1.064 | 4.586 | 5.094 | 4.258 | 40 | 180 | 20 | P
| 5     | 5      | 6.667 | 1.064 | 4.586 | 5.094 | 4.258 | 100 | 150 | 10 | P

A. Case II. 15 Unit Systems

The information of 15 unit system is presented in [18]. The load demand of the system is 2630 MW. The loss coefficients matrix is shown in [19]. Also Table 3, shows the numerical results of this case study in comparison with other techniques.

B. Case II. 15 Unit Systems

The information of 15 unit system is presented in [20]. The load demand of the system is 2630 MW. The loss coefficients matrix is shown in [19]. The feasibility of the proposed method has been compared in terms of solution quality and computation efficiency with PSO [20], Hybrid GAPSO [13], IPSO [20], SOH-PSO [12]. Also convergence characteristic for this case study is shown in Fig.5.

![Figure 5. Convergence characteristic of 15-unit system](image)

C. Case III. 40 Unit Systems

The load demand of the system is 10500 MW. The unit characteristics like cost coefficients along with valve-point loading coefficient, operating limits of generators are given in [4]. The achieved numerical results from proposed SPGSA method are presented in table 4 in comparison via BBO [3], NPSO_LRS [2], SOH_ PSO [12] and other methods. Also convergence characteristic for this case study is shown in Fig.6.

| Table II. IEEE 30-bus system best compromise solutions |
|----------------|----------------|----------------|----------------|----------------|
| MOPO           | MODE           | SPGSA          | No. Gen        |
| 0.9768         | 0.2107         | 0.1721         | P
| 0.4184         | 0.30659        | 0.3638         | P
| 0.64404        | 0.68878        | 0.6839         | P
| 0.75147        | 0.67937        | 0.6512         | P
| 0.44620        | 0.58218        | 0.6077         | P
| 0.48973        | 0.38691        | 0.3563         | P

| Table III. Best simulation results of 15-unit system, P = 2630 MW |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Unit power output (MW) | PSO            | Hybrid GAPSO  | CPSO1          | CPSO2          | SOH_ PSO       | IPSO           | SPGSA          |
| P1               | 439.1162        | 436.8482       | 450.05         | 450.02         | 455.00         | 455.00         | 455.0000       |
| P2               | 407.9727        | 409.6974       | 454.04         | 454.06         | 380.00         | 380.00         | 388.0192       |
| P3               | 119.6324        | 117.0074       | 125.82         | 124.81         | 130.00         | 129.97         | 130.0000       |
| P4               | 129.9925        | 128.2705       | 124.82         | 124.81         | 130.00         | 130.00         | 130.0000       |
| P5               | 151.0681        | 153.3361       | 151.03         | 151.06         | 170.00         | 169.93         | 221.8192       |
| P6               | 459.9978        | 457.4078       | 466.46         | 459.96         | 459.88         | 460.00         | 460.0000       |
| P7               | 425.5601        | 424.4400       | 434.53         | 434.57         | 430.00         | 429.25         | 465.0000       |
| P8               | 98.5699         | 101.1949       | 148.41         | 148.46         | 117.53         | 60.43          | 132.0192       |
| P9               | 113.4936        | 116.1386       | 63.61          | 63.59          | 77.90          | 74.78          | 51.9172        |
| P10              | 101.1142        | 102.2243       | 101.13         | 101.12         | 119.54         | 158.02         | 25.8178        |
| P11              | 33.9116         | 35.0317        | 28.656         | 28.655         | 54.50          | 80.00          | 55.7364        |
| P12              | 79.9583         | 78.8482        | 20.912         | 20.914         | 80.00          | 78.57          | 72.8192        |
| P13              | 25.0042         | 27.1252        | 25.000         | 25.002         | 25.00          | 25.00          | 26.2134        |
| P14              | 41.414          | 37.594         | 54.414         | 54.414         | 17.86          | 15.00          | 25.5263        |
| P15              | 35.614          | 37.0390        | 20.625         | 20.624         | 15.00          | 15.00          | 19.0293        |
| Total cost ($/h) | 2662.1          | 2661.75        | 2662.1         | 2662.29        | 2660.8         | 2659.2        |
| Minimum cost ($/h) | 3285.8        | 3272.24        | 32835          | 32834          | 32751.39       | 32769         | 32685.928     |
| Ploss            | 32.4306         | 31.75          | 32.1302        | 32.1303        | 32.28          | 30.858        | 29.362511      |
| Mean cost ($/h)  | 33039           | 32984          | 33021          | 33021          | 32878          | 32784.5       | 32710.019      |
| Maximum cost ($/h)| 34562.4        | 34865.9        | 33451          | 33450.1        | 32954.4        | 33252.9187    |
The modified form of convergence characteristic of 40-unit system shows advantages of the proposed method. The proposed algorithm applied to three standard IEEE systems to show advantages of proposed algorithm in EED problem, 30-bus 6-generator IEEE test system, 15 units system and 40 units system with valve point effects. The convergence speed of this algorithm is higher than other heuristics algorithms such as NSGA, MODE, MOPSO, etc. and thus the high precision and efficiency are achieved.

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Heidarali Shayanfar received the B.S. and M.S.E. degrees in Electrical Engineering in 1973 and 1979, respectively. He received his Ph. D. degree in Electrical Engineering from Michigan State University, U.S.A., in 1981. Currently, he is a Full Professor in Electrical Engineering Department of Iran University of Science and Technology, Tehran, Iran. His research interests are in the Application of Artificial Intelligence to Power System Control Design, Dynamic Load Modeling, Power System Observability Studies, Voltage Collapse, Congestion Management in a Restructured Power System, Reliability Improvement in Distribution Systems and Reactive Pricing in Deregulated Power Systems. He has published more than 405 technical papers in the International Journals and Conferences proceedings. He is a member of Iranian Association of Electrical and Electronic Engineers and IEEE.