CHAPTER 3

EVOLUTIONARY PROGRAMMING BASED ECONOMIC LOAD DISPATCH PROBLEMS

Introduction

Economic load dispatch problem

Numerical examples, simulation results and analysis

Conclusion
CHAPTER 3
EVOLUTIONARY PROGRAMMING BASED ECONOMIC LOAD DISPATCH PROBLEMS

3.1 INTRODUCTION

The main aim of electric power utilities is to provide high-quality, reliable power supply to the consumers at the lowest possible cost while operating to meet the limits and constraints imposed on the generating units. This formulates the economic load dispatch (ELD) problem for finding the optimal combination of the output power of all the online generating units that minimizes the total fuel cost, while satisfying an equality constraint and a set of inequality constraints. As the cost of power generation is exorbitant, an optimum dispatch results in economy. Practically, the real world input–output characteristics of the generating units are highly nonlinear, non smooth and discrete in nature owing to prohibited operating zones, ramp rate limits and multi fuel effects. Thus the resultant ELD is a challenging non convex optimization problem, which is difficult to solve using the traditional methods.

Combined cycle cogeneration plants can play increasingly important role in the power industry. They have both gas turbines and steam turbines with the following advantages over the conventional thermal plants,

(i) higher overall thermal efficiency
(ii) minimum air pollution by NOx, dust etc.
(iii) independent operation of gas turbines for peak loads
(iv) quick start-up and less capital cost per KW and
(v) less water requirement per unit of electrical output.

The fuel consumption and cost characteristics of such plants are not differentiable. Discontinuity of these curves may also be observed in steam based power plants due to valve point loading. The proposed evolutionary programming
method has been proved to be effective and quite robust in solving such type of optimization problems. It can provide near global optimal solution and handles effectively the discrete control variables. This chapter presents the application of EP method for solving the economic load dispatch of the following test cases:

(i) Three unit thermal plant system

(ii) Three unit thermal plant system in which one unit is a combined cycle co-generation plant

For the first test case the results obtained by the proposed algorithm is compared with the conventional method and GA method for both loss neglected case and loss included cases. The second test case is solved by the proposed algorithm and the results are compared with the GA method.

3.2 ECONOMIC LOAD DISPATCH PROBLEM

3.2.1 Problem Description

Economic load dispatch problem is the sub problem of optimal power flow (OPF). The main objective of ELD is to minimize the fuel cost while satisfying the load demand with transmission constraints.

3.2.2 Objective Function

The classical ELD with power balance and generation limit constraints has been formulated [59] as follows.

Minimize \( F_i = \sum_{i=1}^{d} F_i(P_i) \)  

\( F_i(P_i) = a_i P_i^2 + b_i P_i + c_i \) \hspace{1cm} (3.1)

where \( F_i \) is the total fuel cost of generation,
\( F_i(P_i) \) is the fuel cost function of \( i^{th} \) generator,
\( a_i, b_i, c_i \) are the cost coefficients of \( i^{th} \) generator,
\( P_i \) is the real power generation of \( i^{th} \) generator,
\( d \) represents the number of generators connected in the network.
The minimum value of the above objective function has to be found by satisfying the following constraints.

The power balance constraint [59]

$$\sum_{i=1}^{d} P_i = P_D + P_L$$  \hspace{1cm} (3.3)

where $P_D$ is the total load of the system and

$P_L$ is the transmission losses of the system.

The total transmission loss [60]

$$P_L = \sum_{m} \sum_{n} P_{i,m} B_{mm} P_{i,n}$$  \hspace{1cm} (3.4)

where $P_{i,m}$ and $P_{i,n}$ are the real power injections at $m^{th}$ and $n^{th}$ buses and

$B_{mm}$ are the B-coefficients of transmission loss formula.

The inequality constraint on real power generation $P_i$ for each generator [59] is

$$P_i^{\text{min}} \leq P_i \leq P_i^{\text{max}}$$  \hspace{1cm} (3.5)

where $P_i^{\text{min}}$ and $P_i^{\text{max}}$ are, respectively, minimum and maximum values of real power allowed at generator $i$.

**A. Economic Load Dispatch Problem with CCCP**

Cogeneration units play an increasingly important role in the utility industry. The mutual dependencies of the multiple demand and heat-power capacity of the cogeneration units introduce a complication of integrating the system for economic power dispatch. The cost characteristics of CCCP system (two 75 MW gas turbines and one 50 MW steam turbine) [59] is obtained and hence can be found that they are not differentiable. So the lambda-iterative method will fail in obtaining solution for the ELD of the above problem. The solution for this problem is obtained by
formulating the cost equations by curve fitting technique and implementing the proposed EP algorithm for the optimal scheduling of generators.

B. Constraint Satisfaction Technique

To satisfy the equality constraint of equation (3.3), loading of any one of the units is selected as the dependent loading \( P_{du} \), and its present value is replaced by the value calculated according to the following equation [60]:

\[
P_{du} = P_D + P_L - \sum_{i=1, i \neq du}^d P_i
\]

(3.6)

where, \( P_{du} \) can be calculated directly from the equation (3.6) with the known power demand \( P_D \) and the known values of remaining loading of the generators. Therefore, the dispatch solution always satisfies the power balance constraint provided that \( P_{du} \) also satisfies the operation limit constraint as given in equation (3.5). An infeasible solution is omitted and above procedure is repeated until \( P_{du} \) lies within its operational limit. As \( P_L \) also depends on \( P_{du} \), an expression for \( P_L \) can be substituted in terms of \( P_1, P_2, \ldots, P_{du}, \ldots, P_d \) and \( B_{mn} \) coefficients. After substituting \( P_L \) in the equation (3.6), the independent and dependent generator terms are separated to obtain a quadratic equation for \( P_{du} \). The power balance equality condition is exactly met by solving the quadratic equation for \( P_{du} \).

3.2.3 Implementation of EP for ELD solution

The main objective of ELD is to obtain the amount of real power to be generated by each committed generator, while achieving a minimum generation cost within the constraints. The details of the implementation of EP method are summarized in the following subsections.

3.2.3.1 Representation of an Individual String

For an efficient evolutionary method, the representation of chromosome strings of the problem parameter set is important [37]. Since the decision variables of the ELD problems are real power generations, the generation power output of
each unit is represented as a gene, and many genes comprise an individual in the swarm. Each individual within the population represents a candidate solution for an ELD problem. For example, if there are d units that must be operated to provide power to loads, then the i\(^{th}\) individual \(P_i\) can be defined [37] as follows:

\[
P_i = [P_{i1}, P_{i2}, \ldots, P_{id}], \quad i=1, 2, \ldots, n
\]  

(3.7)

where \(n\) means population size, \(d\) is the number of generator, \(P_{id}\) is the generation power output of \(d\)\(^{th}\) unit at individual \(i\). The dimension of a population is \((n \times d)\). These genes in each individual are represented as real values. The matrix representation of a population is as follows:

<table>
<thead>
<tr>
<th>Individual number</th>
<th>(P_{i1})</th>
<th>(P_{i2})</th>
<th>(\ldots)</th>
<th>(P_{i(d-1)})</th>
<th>(P_{id})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>420.03</td>
<td>150.32</td>
<td>(\ldots)</td>
<td>75.12</td>
<td>45.55</td>
</tr>
<tr>
<td>2</td>
<td>390.28</td>
<td>165.35</td>
<td>(\ldots)</td>
<td>80.23</td>
<td>41.93</td>
</tr>
<tr>
<td>(\ldots)</td>
<td>(\ldots)</td>
<td>(\ldots)</td>
<td>(\ldots)</td>
<td>(\ldots)</td>
<td>(\ldots)</td>
</tr>
<tr>
<td>(n)</td>
<td>412.88</td>
<td>156.84</td>
<td>(\ldots)</td>
<td>78.11</td>
<td>42.78</td>
</tr>
</tbody>
</table>

3.2.3.2 Evaluation Function

The evaluation function for evaluating the minimum generation cost of each individual in the population is adopted [37] as follows:

\[
\text{Minimize } F_i = \sum_{i=1}^{d} F_i(P_i)
\]  

(3.8)

3.2.4 Algorithm of the Proposed Method

The search procedure for calculating the optimal generation quantity of each unit is summarized as follows:

1. In the ELD problems the number of online generating units is the ‘dimension’ of this problem. The chromosomes are randomly generated between the maximum and the minimum operating limits of the generators and represented using equation (3.5).
2. To each individual of the population calculate the dependent unit output \( P_{du} \) from the power balance equation and employ the B-coefficient loss formula to calculate the transmission loss \( P_L \) using constraint satisfaction technique.

3. Calculate the evaluation value of each individual \( P_k \) in the population using the evaluation function \( f \), given by equation (3.8).

4. Do the gaussian random mutation for the individuals in the current population

5. Check for the reaching of termination condition. If yes print out the result and terminate the search. Otherwise go to step 2.

3.3 NUMERICAL EXAMPLES, SIMULATION RESULTS AND ANALYSIS

The study has been conducted on test cases with 3-unit thermal and three units system with 1-unit as combined cycle cogeneration plant system. The description of the test systems are described in the following sections.

Test Case 1: Three-Unit Thermal System

The cost coefficients of 3-unit thermal system are taken from [59]. The cost equations are given below in Rs/h:

\[
F_1 = 0.00156 P_1^2 + 7.92 P_1 + 561 \text{ Rs/h} \\
F_2 = 0.00194 P_2^2 + 7.85 P_2 + 310 \text{ Rs/h} \\
F_3 = 0.00482 P_3^2 + 7.97 P_3 + 78 \text{ Rs/h}
\]

\( B_{mn} \) coefficient matrix:

\[
B_{mn} = \begin{bmatrix}
0.000075 & 0.000005 & 0.0000075 \\
0.000005 & 0.000015 & 0.0000100 \\
0.0000075 & 0.000010 & 0.0000450
\end{bmatrix}
\]
The unit operating ranges are

\[ 100 \text{ MW} \leq P_1 \leq 600 \text{ MW} ; \]
\[ 100 \text{ MW} \leq P_2 \leq 400 \text{ MW} ; \]
\[ 50 \text{ MW} \leq P_3 \leq 200 \text{ MW} ; \]

**Test Case 2: Two Thermal Units and One CCCP System**

In this case, the first two units are the same as 3-unit system and the third unit is replaced with a combined cycle cogeneration plant (CCCP). In CCCP, gas and steam turbines are working in combination to generate electric power. CCCP has two 75 MW gas turbine units and one 50 MW steam turbine unit [82]. The fuel cost characteristics of this plant is shown in Fig. 3.1

![Graph showing fuel cost characteristics of CCCP system](image-url)

**Fig. 3.1. Fuel cost characteristics of CCCP system**
By the method of curve fitting, the cost equation for third plant is formed as follows.

\[
F_3 = 8.517 P_3 + 62.75 \text{ Rs/h} \\
= 605.67 \text{ Rs/h} \\
= 24.08 P_3 - 1390.04 \text{ Rs/h} \\
= 9.18 P_3 + 6.829 \text{ Rs/h} \\
= 1452.84 \text{ Rs/h} \\
= 17.62 P_3 - 1660 \text{ Rs/h}
\]

\[
50 \text{ MW} \leq P_3 \leq 63.75 \text{ MW}; \\
63.75 \text{ MW} \leq P_3 \leq 82.875 \text{ MW}; \\
82.875 \text{ MW} \leq P_3 \leq 93.75 \text{ MW}; \\
93.75 \text{ MW} \leq P_3 \leq 157.5 \text{ MW}; \\
157.5 \text{ MW} \leq P_3 \leq 176.625 \text{ MW}; \\
176.625 \text{ MW} \leq P_3 \leq 200 \text{ MW};
\]

To verify the feasibility of the proposed EP method, three different power systems were tested, under the same evaluation function and individual definition. 50 trials were performed to observe the evolutionary process and to compare their solution quality, convergence characteristic, and computation efficiency. From the experiences of many experiments the population size of 20 has been selected for the proposed algorithm to solve the above test cases. For implementing the above algorithm, the simulation studies were carried out on P-IV, 2.4 GHz, 512 MBDDR RAM system in MATLAB environment.

3.3.1 Test Case 1: Three-Unit Thermal System

The economic load dispatch for the first test case with the corresponding loads is given as 585 MW, 700 MW and 800 MW, respectively. The proposed EP method is applied to obtain the minimum generation cost. Table 3.1 provides the results of optimal scheduling of generators obtained by proposed EP method for three thermal units system with losses neglected. Table 3.2, provides a comparison of economic load dispatch results obtained by various optimization methods for a three unit thermal system with losses neglected.
Table 3.1 Optimal scheduling of generators of 3-unit system neglecting losses

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Load Demand $P_D$ (MW)</th>
<th>$P_1$ (MW)</th>
<th>$P_2$ (MW)</th>
<th>$P_3$ (MW)</th>
<th>$F_t$ (Rs/h)</th>
<th>Execution Time (Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>585</td>
<td>268.85</td>
<td>234.2756</td>
<td>81.8141</td>
<td>5821.4</td>
<td>0.1410</td>
</tr>
<tr>
<td>2.</td>
<td>700</td>
<td>322.9244</td>
<td>277.7232</td>
<td>99.3084</td>
<td>6868.4</td>
<td>0.1410</td>
</tr>
<tr>
<td>3.</td>
<td>800</td>
<td>369.9323</td>
<td>315.5234</td>
<td>114.5465</td>
<td>7738.5</td>
<td>0.1560</td>
</tr>
</tbody>
</table>

Table 3.2. Solution of different methods neglecting losses – 3-unit system

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Load Demand $P_D$ (MW)</th>
<th>Conventional Method [59] (Rs/h)</th>
<th>GA Method [59] (Rs/h)</th>
<th>EP Method (Rs/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>585</td>
<td>5821.4000</td>
<td>5827.5</td>
<td>5821.4</td>
</tr>
<tr>
<td>2.</td>
<td>700</td>
<td>6838.4056</td>
<td>6877.2</td>
<td>6838.4</td>
</tr>
<tr>
<td>3.</td>
<td>800</td>
<td>7738.5189</td>
<td>7756.8</td>
<td>7738.5</td>
</tr>
</tbody>
</table>

The above system is solved for a load demand of 585.33 MW using the proposed EP method with the inclusion of transmission loss. The optimal scheduling of generators obtained by the proposed algorithm for a three-unit thermal system was shown in Table 3.3. By following the above procedure, the solution obtained by the proposed method for a three unit thermal unit system with losses included is given in Table 3.4.

Table 3.3. Optimal scheduling of generators including losses – 3-unit system

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Load Demand $P_D$ (MW)</th>
<th>$P_1$ (MW)</th>
<th>$P_2$ (MW)</th>
<th>$P_3$ (MW)</th>
<th>$F_t$ (Rs/h)</th>
<th>Loss, $P_L$ (MW)</th>
<th>Execution Time (Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>585.33</td>
<td>233.2</td>
<td>267.8</td>
<td>90.84</td>
<td>5886</td>
<td>6.95</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Table 3.4. Solution of different methods including losses – 3-unit system

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Load Demand $P_D$ (MW)</th>
<th>Conventional Method [59] (Rs/h)</th>
<th>GA Method [59] (Rs/h)</th>
<th>Proposed EP Method (Rs/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>585.33</td>
<td>5890.06</td>
<td>5890.09</td>
<td>5886.9</td>
</tr>
</tbody>
</table>

Fig. 3.2. shows the convergence characteristics of the proposed algorithm for a load demand ($P_D$) of 585 MW with losses neglected. Fig. 3.3. shows the reliability of the proposed algorithm for different runs of the program. The figure shows that the algorithm is capable of obtaining a faster convergence for the three unit thermal system in a very few generations and the solution is consistent.

![Convergence Property](image)

Fig. 3.2. EP based ELD convergence characteristics – 3-unit system
3.3.2 Test Case 2: Three-Unit System with CCCP

The economic load dispatch is solved using a proposed EP algorithm for a three unit system with CCCP having system load as 680 MW, 750 MW and 869 MW, respectively. Table 3.5. summarizes the optimal dispatch of load among the available generating units. The simulation results were studied and the obtained values of cost of generation of different methods are given in Table 3.6. The cost was found to be minimum in the EP based method.

Table 3.5. Optimal scheduling of generators including CCCP – 3-unit system

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Load Demand (MW)</th>
<th>$P_1$ (MW)</th>
<th>$P_2$ (MW)</th>
<th>$P_3$ (MW)</th>
<th>Loss $P_L$ (MW)</th>
<th>$F_t$ (Rs/h)</th>
<th>Execution Time (Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>680</td>
<td>283.6643</td>
<td>323.1737</td>
<td>82.8777</td>
<td>9.7157</td>
<td>6588.3</td>
<td>0.1560</td>
</tr>
<tr>
<td>2.</td>
<td>750</td>
<td>273.0729</td>
<td>311.4274</td>
<td>176.6250</td>
<td>11.1253</td>
<td>7235.1</td>
<td>0.1410</td>
</tr>
<tr>
<td>3.</td>
<td>869</td>
<td>328.6344</td>
<td>378.8490</td>
<td>176.6274</td>
<td>15.1108</td>
<td>8346.8</td>
<td>0.1570</td>
</tr>
</tbody>
</table>
Table 3.6. Solution of different methods including CCCP – 3-unit system

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Load Demand (MW)</th>
<th>GA Method (Rs/h) [59]</th>
<th>Proposed EP Method (Rs/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>680</td>
<td>6639.47</td>
<td>6588.3</td>
</tr>
<tr>
<td>2.</td>
<td>750</td>
<td>7267.93</td>
<td>7235.1</td>
</tr>
<tr>
<td>3.</td>
<td>869</td>
<td>8398.07</td>
<td>8346.8</td>
</tr>
</tbody>
</table>

3.4 CONCLUSION

In this chapter the proposed EP method is applied for solving the economic load dispatch of power system with and without combined cycle cogeneration plants. If the power system has combined cycle cogeneration plants, the proposed algorithm can easily solve the economic load dispatch problem. From the comparison of results for the test cases, it is proved that the proposed algorithm is performing better than the conventional method and genetic algorithm method in the aspects of fuel cost as well as computation time.