CHAPTER 6

ECONOMIC LOAD DISPATCH PROBLEM WITH CCCP

6.1 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 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 startup 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 (Venkatesh et al 2000). The proposed bacteria foraging algorithm 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 BFA for solving the economic load dispatch of the following test cases:

(i) Three units thermal plant system

(ii) Three units thermal plant system in which one unit is a combined cycle cogeneration 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.

6.2 ECONOMIC LOAD DISPATCH PROBLEM

6.2.1 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.
6.2.2 Objective Function

The classical ELD with power balance and generation limit constraints has been formulated (Fogel 1997) as follows.

Minimize \( F_i = \sum_{i=1}^{d} F_i(P_i) \) \( (6.1) \)

\( F_i(P_i) = a_i P_i^2 + b_i P_i + c_i \) \( (6.2) \)

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 (Venkatesh et al 2000)

\[ \sum_{i=1}^{d} P_i = P_D + P_L \] \( (6.3) \)

where \( P_D \) is the total load of the system and

\( P_L \) is the transmission losses of the system.

The total transmission loss (Sudhakaran et al 2005)

\[ P_L = \sum_m \sum_n P_{i,m} B_{mn} P_{i,n} \] \( (6.4) \)
where $P_{i,m}$ and $P_{i,n}$ are the real power injections at $m^{th}$ and $n^{th}$ buses and $B_{mn}$ are the B-coefficients of transmission loss formula.

The inequality constraint on real power generation $P_i$ for each generator (Sudhakaran et al 2005) is

$$P_i^\text{min} \leq P_i \leq P_i^\text{max}$$

(6.5)

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) (Fogel 1997) 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 algorithm for the optimal scheduling of generators.

B. Constraint Satisfaction Technique

To satisfy the equality constraint of Equation (6.3), 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
\[ P_{du} = P_D + P_L - \sum_{i=1,i \neq du}^{d} P_i \]  

(6.6)

where, \( P_{du} \) can be calculated directly from the Equation (6.6) 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 (6.5). 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 (6.6), 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 \( P_{du} \).

6.2.3 Implementation of BFA 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 BFA are summarized in the following subsections.

6.2.3.1 Representation of an individual string

For an efficient evolutionary method, the representation of strings of the problem parameter set is important (Sudhakaran et al 2005). Since the decision variables of the ELD problems are real power generations, the generation power output of each unit is represented as control variable and concatenated to form an individual called bacteria. 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 $P_{gi}$ can be defined as follows:

$$P_{gi} = [P_{i1}, P_{i2}, \ldots, P_{id}], \quad i = 1, 2, \ldots, n$$  \hspace{1cm} (6.7)

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 control variables in each individual are represented as real values. The matrix representation of a population is as follows:

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

6.2.3.2 Evaluation function

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

$$\text{Minimize } F_i = \sum_{i=1}^{d} F_i(P_i)$$ \hspace{1cm} (6.8)

6.2.4 Algorithm Steps 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 bacteria are randomly generated between the maximum and the minimum operating limits of the generators and represented using Equation (6.5).

2. To each individual of the population calculate the dependent unit output $P_{du}$ from the power balance equation and employ the $B_{mn}$ coefficient loss formula to calculate the transmission loss $P_L$ using constraint satisfaction technique.

3. Calculate the evaluation value of each individual $P_i$ in the population using the evaluation function $f$, given by Equation (6.8).

4. Do operators of BFA 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.

6.3 NUMERICAL EXAMPLES, SIMULATION RESULTS AND ANALYSIS

The study has been conducted on test cases with 3-units 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-Units Thermal System**

The cost coefficients of 3-units thermal system are taken from (Venkatesh et al 2000). The cost equations are given below in Rs/h:
\[ F_1 = 0.00156 P_1^2 + 7.92 P_1 + 561 \text{ Rs/h} \]

\[ F_2 = 0.00194 P_2^2 + 7.85 P_2 + 310 \text{ Rs/h} \]

\[ F_3 = 0.00482 P_3^2 + 7.97 P_3 + 78 \text{ Rs/h} \]

\[
B_{mn} \text{ coefficient matrix:} \\
\begin{bmatrix}
0.000075 & 0.000005 & 0.0000075 \\
0.000005 & 0.000015 & 0.0000100 \\
0.0000075 & 0.000010 & 0.0000450
\end{bmatrix}
\]

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-units system and the third unit is replaced with a 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 (Venkatesh et al 2000). The fuel cost characteristics of this plant is shown in Figure 6.1.
By the method of curve fitting, the cost equation for third plant is formed as follows.

\( F_3 = 8.517P_3 + 62.75 \text{Rs/h} \)  \( 50 \text{MW} \leq P_3 \leq 63.75 \text{MW}; \)
\( = 60567 \text{Rs/h} \)  \( 63.75 \text{MW} \leq P_3 \leq 82.875 \text{MW}; \)
\( = 24.08P_3 - 139004 \text{Rs/h} \)  \( 82.875 \text{MW} \leq P_3 \leq 93.75 \text{MW}; \)
\( = 9.18P_3 + 6.829 \text{Rs/h} \)  \( 93.75 \text{MW} \leq P_3 \leq 157.5 \text{MW}; \)
\( = 145284 \text{ Rs/h} \)  \( 157.5 \text{MW} \leq P_3 \leq 176625 \text{MW}; \)
\( = 17.62P_3 - 1660 \text{Rs/h} \)  \( 176625 \text{MW} \leq P_3 \leq 200 \text{MW}; \)

To verify the feasibility of the proposed BFA method, 50 trials were performed to observe the evolutionary process and to compare their solution quality, convergence characteristics and computation efficiency. From the experiences of many experiments the population size of 20 bacterium 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 Intel(R) Core(TM) i5-2450M CPU @ 2.5 GHz in MATLAB environment.

6.3.1 Test Case 1: Three-Units Thermal System

The economic load dispatch for the first test case with the corresponding loads is given as 812.57 MW, 585.33 MW and 869 MW, respectively. The proposed BFA method is applied to obtain the minimum generation cost. Table 6.1 provides the results of optimal scheduling of generators obtained by proposed method for three thermal units system. Table 6.2 provides a comparison of economic load dispatch results obtained by various optimization methods for a three units thermal system.

Table 6.1 Optimal scheduling of generators of 3-units system by BFA method

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Load Demand Pd (MW)</th>
<th>P1 (MW)</th>
<th>P2 (MW)</th>
<th>P3 (MW)</th>
<th>PL (MW)</th>
<th>Total cost (Rs/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>812.57</td>
<td>352.562</td>
<td>370.736</td>
<td>129.845</td>
<td>13.573</td>
<td>7985.850</td>
</tr>
<tr>
<td>2.</td>
<td>585.33</td>
<td>233.423</td>
<td>267.802</td>
<td>91.071</td>
<td>6.967</td>
<td>5889.910</td>
</tr>
<tr>
<td>3.</td>
<td>869.00</td>
<td>347.969</td>
<td>396.893</td>
<td>139.677</td>
<td>15.540</td>
<td>8522.289</td>
</tr>
</tbody>
</table>
Table 6.2 Comparison of test results obtained by GA, classical Kirchmayer method and BFA – 3-units system

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>812.57</td>
<td>7986.093</td>
<td>7986.068</td>
<td>7985.850</td>
<td></td>
</tr>
<tr>
<td>585.33</td>
<td>5890.063</td>
<td>5890.094</td>
<td>5889.910</td>
<td></td>
</tr>
<tr>
<td>869.00</td>
<td>8522.450</td>
<td>8522.875</td>
<td>8522.289</td>
<td></td>
</tr>
</tbody>
</table>

6.3.2 Test Case 2: Three-Units System with CCCP

The economic load dispatch is solved using a proposed BFA algorithm for a three units system with CCCP having system load as 680 MW, 750 MW and 869 MW, respectively. Table 6.3 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 6.4. The cost was found to be minimum in the BFA based method.

Table 6.3 Optimal scheduling of generators including CCCP – 3-units 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>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>680</td>
<td>287.43</td>
<td>319.52</td>
<td>82.87</td>
<td>9.84</td>
<td>6588.38</td>
</tr>
<tr>
<td>2.</td>
<td>750</td>
<td>272.62</td>
<td>311.85</td>
<td>176.62</td>
<td>11.11</td>
<td>7235.09</td>
</tr>
<tr>
<td>3.</td>
<td>869</td>
<td>329.53</td>
<td>377.98</td>
<td>176.62</td>
<td>15.14</td>
<td>8346.84</td>
</tr>
</tbody>
</table>
### Table 6.4 Solution of different methods including CCCP – 3-units system

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Load Demand (MW)</th>
<th>GA Method (Rs/h) [50]</th>
<th>Proposed BFA (Rs/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>680</td>
<td>6639.47</td>
<td>6588.38</td>
</tr>
<tr>
<td>2.</td>
<td>750</td>
<td>7267.93</td>
<td>7235.09</td>
</tr>
<tr>
<td>3.</td>
<td>869</td>
<td>8398.07</td>
<td>8346.84</td>
</tr>
</tbody>
</table>

### 6.4 CONCLUSION

In this chapter the proposed bacteria foraging algorithm was applied for solving the economic load dispatch of power system with and without combined cycle cogeneration plants. In Table 6.1, the total fuel cost obtained by the proposed bacteria foraging algorithm has been tabulated for a power demands of 812.57 MW, 585.33 MW and 869 MW. The solution obtained by the proposed method resulted in less fuel cost and was compared with other methods as shown in Table 6.2. For the three units system with CCCP, the ELD solution has been obtained for the power demands of 680 MW, 750 MW and 869 MW. The proposed BFA resulted in less fuel cost and the comparisons of results have been done as shown in Table 6.4. 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 superior in the aspects of fuel cost as well as computation time.