CHAPTER 3

EVOLUTIONARY PROGRAMMING BASED ECONOMIC DISPATCH OF GENERATORS WITH PROHIBITED OPERATING ZONES

3.1 INTRODUCTION

Economic dispatch is one of the most important problems to be solved in the operation of power systems. The traditional methods such as lambda-iteration method, the base point and participation factors method and gradient method are well known for the economic dispatch of generators. All these methods consider the economic dispatch problem as a convex optimization problem and it assumes that the whole of the unit operating range between the minimum generation limit ($P_{\text{min}}$) and the maximum generation limit ($P_{\text{max}}$) is available for operation.

In practical systems however, the whole of the unit operating range is not always available for operation. Some of the on-line units may have prohibited operating zones due to physical operational limitations. Units can have prohibited zones due to amplified vibrations in a shaft bearing in a certain operating regions, faults in the machines themselves or the associated auxiliaries, such as boilers, feed pumps etc. The operation of units in these zones leads to instabilities, rendering them unable to carry any load for any
appreciable time. Hence the avoidance of operation in these zones will improve the economic condition and performance.

When a unit has prohibited zones, it will be operated only above or below them. The prohibited operating zones of a unit divide the operating range between its minimum and maximum generation limits into several disjoint convex sub-regions. These disjoint sub-regions form a non-convex decision space and the associated economic dispatch problem is thus a non-convex optimization problem. Hence traditional methods cannot be directly applied to solve the dispatch problem with prohibited operating zones. The fuel cost curve of an unit with prohibited operating zones is a discontinuous function as shown in Figure 3.1.

Figure 3.1 Unit input – output characteristic with prohibited operating zones
The disjoint convex sub-regions that form a non-convex decision space results in multiple decision spaces for the economic dispatch problem. Each of the decision space can be either feasible or infeasible with respect to the system demand. The feasible optimal solution of the dispatch problem can only reside in one of the feasible spaces. This can be found by using the conventional $\lambda-\delta$ iterative search method for each of the feasible spaces. However, for a system with a large number of feasible decision spaces, such an exhaustive search requires large computing time. The dynamic programming based method would not be practical due to its heavy computational burden. The Branch-and-Bound method has improvements over the dynamic programming method, but requires a large number of heuristic case evaluations.

Several researchers have developed ways to circumvent this problem. These involve carrying out some additional computations to determine the region of feasible solution and then resorting to conventional optimization techniques.

Lee and Breipohl (1993) proposed a method that decomposes the non-convex decision space into a small number of subsets that form multiple decision spaces, then used an approach that selects a small set of classified feasible decision spaces and thereafter determines the feasible optimal solution using the conventional $\lambda-\delta$ iterative method. This approach has the problem of having to use the $\lambda-\delta$ iterative method repeatedly on each of the classified feasible decision spaces. This requires large computation time if many on-line units have prohibited zones that increase the number of decision spaces.
Fan and McDonald (1994) proposed a new method that defined a small and advantageous set of decision spaces by analyzing the desired optimal solution without considering the prohibited zones. They used an efficient algorithm to determine the most advantageous space and thereafter utilized the conventional $\lambda-\delta$ iterative method to find the feasible optimal dispatch solution. The method proposed by them required only two executions of the $\lambda-\delta$ iterative dispatch. Its effectiveness was illustrated through extensive testing on several example dispatch problems.

Orero and Irving (1996) presented a non-traditional stochastic approach that uses genetic algorithms for solving these problems in which penalty terms are incorporated in the fitness function for all unit loadings falling within prohibited zones. The penalty terms which have been introduced reduce the fitness of the fuel cost function according to the magnitude of the violation. Since the penalty term has a vital effect on the performance of the algorithms, its careful selection and grading that combines well with the cost function is a difficult task. Chen and Chang (1995) also used genetic algorithms in which equal incremental cost criterion is the basis to solve the large scale economic dispatch problem that has ramp rate limits in addition to prohibited zones. The authors developed a heuristic algorithm to adjust the generation output of a unit in order to avoid its operation in the prohibited zones.

In this chapter an innovative approach that uses evolutionary programming for solving economic dispatch problems when some or all of the units have prohibited operating zones is proposed. The main advantage of the method is its ability to account for prohibited operating zones without the extra mathematical operations that are necessary in other methods to deal with
the complication of discontinuities in cost functions. Unlike the traditional methods (Lee et al, 1993; Fan et al, 1994), it requires neither the decomposition of the non-convex decision space nor the determination of the advantageous set of decision spaces.

3.2 PROBLEM FORMULATION

The objective of economic dispatch is to determine the generation levels for all on-line units which minimizes the total fuel cost, while satisfying a set of constraints. It can be formulated as follows:

3.2.1 Fuel cost

The fuel cost function of a generating unit is usually described by a quadratic function of power output $P_j$ as:

$$F_j(P_j) = a_j P_j^2 + b_j P_j + c_j$$

where $a_j$, $b_j$ and $c_j$ are the cost coefficients of unit $j$.

The objective is to minimize the cost function

$$\text{Minimize } F = \sum_{j \in \Omega} F_j(P_j)$$

where $\Omega$ is the set of all on-line units, subject to the constraints given as follows:
3.2.2 Power balance constraint

The total generation must supply the demand and compensate for the transmission losses in the system

$$\sum_{j \in \Omega} P_j = P_D + P_L$$  \hspace{1cm} (3.3)

where $P_D$ is the load demand and $P_L$ is the transmission losses.

The transmission losses must be taken into account to achieve true economic dispatch. Transmission loss is a function of unit generations. To calculate losses, the penalty factors method and B-coefficients method are in general use (Chen and Chang, 1995). In the latter method, commonly used by the power utility industry, the network losses are expressed as a quadratic function.

$$P_L = \sum_{i=1}^{n} \sum_{j=1}^{n} P_i B_{ij} P_j$$  \hspace{1cm} (3.4)

where $B_{ij}$ are constants called B coefficients or loss coefficients and $n$ is the total number of generating units in the system. The B coefficients method is used for this study.

3.2.3 Capacity limits constraint

$$P_{j,\text{min}} \leq P_j \leq P_{j,\text{max}} \forall j \in (\Omega - \theta)$$  \hspace{1cm} (3.5)

where $\theta$ is the set of on-line units which have prohibited operating zones.
\( \Omega - \theta \) is the set of on-line units that do not have prohibited operating zones and \( P_{j,\min} \) and \( P_{j,max} \) are the minimum and maximum generation limits.

### 3.2.4 Prohibited operating zone constraint

\[
\begin{align*}
P_{j,\min} & \leq P_j \leq P^1_{j,1} \\
P^u_{j,k-1} & \leq P_j \leq P^u_{j,k} \quad k = 2, \ldots, z_j \\
P^d_{j,k} & \leq P_j \leq P^d_{j,max}
\end{align*}
\]

for all \( j \in \theta \)  \( \text{(3.6a)} \)

where \( P^u_{j,k} \) and \( P^d_{j,k} \) are lower and upper bounds of the \( k^{th} \) prohibited zone of unit \( j \) and \( z_j \) is the number of prohibited zones of unit \( j \).

### 3.2.5 Spinning reserve constraint

Let \( S_j \) be the unit \( j \)'s spinning reserve contribution, \( P_j \) be unit \( j \)'s effective upper generation limit, \( S_R \) be the total spinning reserve requirement and \( S_{j,max} \) be unit \( j \)'s maximum spinning reserve contribution. Then the spinning reserve constraint is stated as follows:

\[
\sum_{j \in \Omega} S_j \geq S_R
\]

\( \text{(3.7a)} \)

where

\[
\begin{align*}
S_j &= \min \{ P_{j,\max} - P_j, S_{j,\max} \}, \quad \forall j \in (\Omega - \theta) \\
S_j &= 0, \quad \forall j \in \theta
\end{align*}
\]

\( \text{(3.7b)} \)

The spinning reserve constraint restricts only the physical upper generation limit to effective upper limit in generators that do not have
prohibited zones. The effective upper generation limit can be determined by the following equations.

\[
\sum_{j \in (\Omega - \theta)} \bar{P}_j = \left[ \sum_{j \in (\Omega - \theta)} P_{j, \text{max}} \right] - S_R \tag{3.7c}
\]

\[
\text{Max}[P_{j, \text{max}} - S_j, \text{max}, P_{j, \text{min}}] \leq \bar{P}_j \leq P_{j, \text{max}} \quad \forall j \in (\Omega - \theta) \tag{3.7d}
\]

3.2.6 Ramp-rate constraint

The ramp-rate constraint restricts the operating range of the physical lower and upper limit to the effective lower limit \( \underline{P}_j \) and upper limit \( \overline{P}_j \) respectively. These limits are defined as

\[
\underline{P}_j = \max[P_{j, \text{min}}, P_j^0 - DR_j] \tag{3.8a}
\]

\[
\overline{P}_j = \min[P_{j, \text{max}}, P_j^0 + UR_j] \tag{3.8b}
\]

where \( P_j^0 \) is the power generation of unit \( j \) at previous hour and \( DR_j \) and \( UR_j \) are the ramp-rate limits of unit \( j \) as generation decreases and increases respectively. Hence the ramp rate constraint is stated as

\[
\underline{P}_j \leq P_j \leq \overline{P}_j \tag{3.8c}
\]

The prohibited operating zone constraints (3.6a, 3.6b and 3.6c) avoids the operation of units in the prohibited zones. The prohibited zones \( z_j \) of the dispatchable units divide the operating region between the minimum and maximum generation limits into \( z_j + 1 \) disjoint operating sub-regions.
3.3 SOLUTION METHODOLOGY

The main stages of the evolutionary programming approach include initialization, mutation, and competition and selection. Its implementation for economic dispatch of generators is given as below:

3.3.1 Initialization

The initial population is one of the key factors in deciding the quickness of reaching the optimum in any evolutionary programming approach. This quick progress towards the solution is achieved by generating the initial population within the feasible operating range, thus avoiding altogether power generation in the prohibited zones. Hence the requirement of power generation of units confined only to the operating zones is satisfied by the initial population itself.

The initial population is composed of K parent individuals. The elements of a parent are randomly created permutation of power outputs of the generating units. Each element in a population is uniformly distributed within its feasible range. The innovative approach used to generate the initial population that satisfies all constraints given in section 3.2 is given below:

- For units with whole of its operating range available for operation, $P_j$ is uniformly distributed generation level ranging over $[P_{j,\text{min}}, P_{j,\text{max}}]$.
- For all units with prohibited operating zones, a random integer $u_r$ between 1 and $z_j+1$ (including both) is first generated. This random integer indicates the operating sub-region of unit j in which its
generation level must fall. If \( u_r = 1 \), generation \( P_j \) must satisfy the constraint given in eqn. (3.6a). The random number \( u_r = z_j + 1 \) corresponds to \( P_j \), subjected to the constraint eqn. (3.6c). All intermediate random numbers result in generation levels constrained by eqn. (3.6b).

- If a unit has spinning reserve requirement or ramp-rate limits, its power output is uniformly distributed between its effective lower and upper limits.

By this type of initialization procedure, a small population size itself is adequate to yield the optimum solution in lesser computation time. The initialized parent vectors are

\[
p_i = [P_1, P_2, \ldots, P_n] \quad i = 1, 2, \ldots, K
\]

In order to get exact balance between power generation and load demand, one of the generators without prohibited operating zones (if any) and with largest operating range is arbitrarily selected as a dependent unit. Its output is calculated according to:

\[
P_d = P_D + P_L - \sum_{j=1}^{n} P_j
\]

The power loss \( P_L \) can be found through the use of the B-matrix loss coefficients (Yang et al, 1996). Since \( P_L \) is also a function of \( P_d \), there will be two solutions for \( P_d \). Depending upon the nature of solutions, \( P_d \) is selected as follows:
a) If only one solution is within the limits, that solution is $P_d$.
b) If both the solutions are within the limits, the one with lesser fitness value is chosen as $P_d$.

3.3.2 Mutation

Mutation is performed on each vector element by adding a normally distributed random number with mean zero and standard deviation $\sigma_j$ denoted as $N(0,\sigma_j^2)$. This results in

\begin{align*}
p'_i &= [P'_{1}, P'_{2}, ..., P'_{n}] \quad \text{for } i = 1,2,... K \\
P'_j &= P_j + N(0,\sigma_j^2) \quad \text{for } j = 1,2,...,n
\end{align*}

(3.11a)

(3.11b)

\begin{equation}
\sigma_j = \beta \frac{f_i}{f_{\text{max}}} \quad \text{(3.11c)}
\end{equation}

where $\beta$ is the scaling factor which has to be tuned during the process of search for the optimum,

$f_i$ is the fitness value of the $i^{th}$ individual, and

$f_{\text{max}}$ is the maximum fitness among the $K$ parents.

Mutation results in creation of $K$ offspring individuals.

The initial parent individuals contain elements generated only within the operating sub-regions. However, after mutation the elements of offspring $P'_j$ may violate one or all the constraints.
The violation of the capacity limits constraint in eqn. (3.5) is corrected as follows:

\[
P'_j = \begin{cases} 
P_{j,\text{min}} & \text{if } P'_j < P_{j,\text{min}} \\
P_{j,\text{max}} & \text{if } P'_j > P_{j,\text{max}} \end{cases} \quad (3.12a)
\]

Similarly, if the output of the dependent generator violates its limits, it is fixed as follows:

\[
P_{d,m} = \begin{cases} 
P_{d,\text{min}} & \text{if } P'_d < P_{d,\text{min}} \\
P_{d,\text{max}} & \text{if } P'_d > P_{d,\text{max}} \end{cases} \quad (3.12b)
\]

If the prohibited operating zone constraint as given in eqn. (3.6) is violated, instead of introducing a penalty term in the fitness function, the midpoints of the prohibited zones for each unit are calculated. For a generation level \( P'_j \) lying between \( P_{j,m} \) and \( P'_{j,m} \) of prohibited zone \( m \), the midpoint \( M_{j,m} \) of the prohibited zone \( m \) is:

\[
M_{j,m} = \frac{P''_{j,m} + P'_{j,m}}{2} \quad m = 1, 2, ..., z_j
\]

and

\[
P'_j = \begin{cases} 
P'_{j,m} & \text{if } P'_j < M_{j,m} \\
P''_{j,m} & \text{if } P'_j > M_{j,m} \end{cases} \quad (3.13)
\]

The generation level \( P'_j \) is assigned the boundary value of the prohibited zone to which it is driven to by mutation. By doing so, it is accepted as a feasible
solution. This is in contrast to the penalty term approach which increases the probability of it being rejected as an infeasible solution. Fixing the generation levels with respect to the mid-points of the prohibited operating zones (3.13) makes the economic dispatch problem to converge more quickly.

If the units constrained by either spinning reserve requirement or ramp-rate limits violate their limits then the eqn (3.12a) after the replacement of $P_{j,\text{min}}$ and $P_{j,\text{max}}$ with $P_j$ and $P_j$ respectively, has to be satisfied.

After limiting the power output of the dependent generator as given in eqn. (3.12b), a penalty term is introduced in the objective function (eqn. 3.2) to penalize its fitness value, and hence eqn. (3.2) is changed to the following generalized form as:

$$\min f = \sum_{j \in \Omega} F_j(P_j) + \phi [P_d - P_{d,\text{lim}}]^2$$  \hspace{1cm} (3.14)

where $\phi$ is a penalty coefficient.

The second term in eqn. (3.14) is equal to zero during initialization and it gets non-zero value after mutation only if $P_d$ violates its minimum and maximum generation limits.

The initial population and their offspring created by mutation form a combined population of $2K$ individuals.
3.3.3 Competition and selection

The 2K individuals compete with each other for selection. A weight value \( w_i \) is assigned to each individual as follows:

\[
W_i = \frac{X_{wi}}{t=1} \tag{3.15a}
\]

\[
w_i = 1 \text{ if } u < \frac{f_t}{f_t + f_i} \tag{3.15b}
\]

\[
w_i = 0 \text{ otherwise} \tag{3.15c}
\]

where \( f_i \) is the fitness of the \( i^{th} \) competitor randomly selected from 2K individuals, and \( u \) is a uniform random number ranging over [0,1]. While computing the weight for each individual it is ensured that each individual is selected only once from the combined population. Even though relative fitness values are used during the process of mutation, competition and selection, it leads to slow convergence. This is because the ratio \( f_i / (f_i + f_t) \) is always around 0.5 and not uniformly distributed between 0 and 1. Hence the following strategy is adopted to assign the weights:

\[
w_i = 1 \text{ if } \frac{f_t}{f_t + f_i} > 0.5 \tag{3.15d}
\]

\[
w_i = 0 \text{ otherwise} \tag{3.15e}
\]

This weight assignment is found to be efficient as it yields proper selection and good convergence. When all the 2K individuals obtain their weights
they are ranked in descending order and the first K individuals are selected as parents along with their fitness values for next generation.

The steps in sections 3.3.2 and 3.3.3 are repeated until there is no appreciable improvement in the minimum fitness value.

3.4 EXAMPLES AND PERFORMANCE ANALYSIS

To test the effectiveness of the evolutionary programming approach, it has been applied on a few sample economic dispatch problems. Only relative fitness values are used in the process of mutation and competition and selection for all the examples given. The optimal solution obtained is almost the same for each example over a wide range of values of scaling factor and population size. The convergence is fast and optimal solution is reached in few iterations in almost all the examples tested.

Example 1

A sample system of three thermal units (Chen et al, 1995) is considered. The unit characteristics are given in Tables 3.1 and 3.2. Each unit has prohibited operating zones as well as ramp-rate limits. The power loss is taken into account through the use of loss-formula coefficients given below:

\[
B_B = \begin{bmatrix}
0.0001360 & 0.0000175 & 0.000184 \\
0.0000175 & 0.0001540 & 0.000283 \\
0.0001840 & 0.0002830 & 0.001610
\end{bmatrix}
\]

The system load demand is 300 MW.
Table 3.1 Generating units' capacity and cost coefficients

<table>
<thead>
<tr>
<th>Unit</th>
<th>$P_{j,\text{min}}$ (MW)</th>
<th>$P_{j,\text{max}}$ (MW)</th>
<th>$a_j$ ($$/M\text{W}^2\text{hr}$)</th>
<th>$b_j$ ($$/M\text{W}\text{hr}$)</th>
<th>$c_j$ ($$/\text{hr})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>250</td>
<td>0.00525</td>
<td>8.663</td>
<td>328.13</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>150</td>
<td>0.00609</td>
<td>10.04</td>
<td>136.91</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>100</td>
<td>0.00592</td>
<td>9.76</td>
<td>59.16</td>
</tr>
</tbody>
</table>

Table 3.2 Generating units’ ramp-rate limits and prohibited zones

<table>
<thead>
<tr>
<th>Unit</th>
<th>$P_j^0$ (MW)</th>
<th>$U_R_j$ (MW/hr)</th>
<th>$D_R_j$ (MW/hr)</th>
<th>Prohibited Zones (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>215</td>
<td>55.0</td>
<td>95.0</td>
<td>[105,117] [165,177]</td>
</tr>
<tr>
<td>2</td>
<td>72.0</td>
<td>55.0</td>
<td>78.0</td>
<td>[50,60] [92,102]</td>
</tr>
<tr>
<td>3</td>
<td>98.0</td>
<td>45.0</td>
<td>64.0</td>
<td>[25,32] [60,67]</td>
</tr>
</tbody>
</table>

The effective lower and upper generation limits are computed based on eqns. (3.8a), (3.8b) and (3.8c) and are listed in Table 3.3.

Table 3.3 Effective lower and upper generation limits

<table>
<thead>
<tr>
<th>Unit</th>
<th>$P_j$ (MW)</th>
<th>$\bar{P}_j$ (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120</td>
<td>250</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>127</td>
</tr>
<tr>
<td>3</td>
<td>34</td>
<td>100</td>
</tr>
</tbody>
</table>
The ramp-rate limits restrict the operating range of units to the effective generation limits. Thus, only the prohibited zones within the effective generation limits need to be considered as given in Table 3.4:

Table 3.4 Prohibited zones within effective generation limits

<table>
<thead>
<tr>
<th>Unit</th>
<th>Zone 1 (MW)</th>
<th>Zone 2 (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>[165,177]</td>
</tr>
<tr>
<td>2</td>
<td>[50,60]</td>
<td>[92,102]</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>[60,67]</td>
</tr>
</tbody>
</table>

Table 3.5 presents the results obtained by applying the proposed evolutionary programming approach as against the genetic algorithms approach presented in Chen et al (1995).

Table 3.5 Unit power output levels, power loss and optimal fuel cost

<table>
<thead>
<tr>
<th></th>
<th>( P_1 ) (MW)</th>
<th>( P_2 ) (MW)</th>
<th>( P_3 ) (MW)</th>
<th>Power Loss (MW)</th>
<th>Fuel Cost ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP approach</td>
<td>203.163</td>
<td>75.220</td>
<td>34.631</td>
<td>13.014</td>
<td>3635.662</td>
</tr>
<tr>
<td>GA approach</td>
<td>194.265</td>
<td>50.000</td>
<td>79.627</td>
<td>24.011</td>
<td>3737.167</td>
</tr>
</tbody>
</table>

The parameters used in the proposed evolutionary programming approach are as follows:

- scaling factor : 0.01
- population size : 20
- maximum generation number : 1
From Table 3.5, it is clear that the solution obtained by the proposed evolutionary programming approach is superior to that obtained by genetic algorithm approach as it gives a substantial saving of 101.5 $/hr.

Example 2

A four unit system with the following input-output characteristics (Lee et al, 1993) is considered. The cost function is

\[ F_j(P_j) = 500 + 10 P_j + 0.001 P_j^2 \]$/$hr$

and operating limits are:

\[ 100 \text{ MW} \leq P_j \leq 500 \text{ MW}, S_{j\text{max}} = 50 \text{ MW}, \quad j = 1, 2, 3, 4 \]

Units 1 and 2 have prohibited zones which are described in Table 3.6.

<table>
<thead>
<tr>
<th>Table 3.6 Prohibited zones</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Unit</th>
<th>Zone 1 (MW)</th>
<th>Zone 2 (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[200,250]</td>
<td>[300,350]</td>
</tr>
<tr>
<td>2</td>
<td>[210,260]</td>
<td>[310,360]</td>
</tr>
</tbody>
</table>

The system load demand is 1375 MW and the total spinning reserve requirement is 100 MW.

Based on eqns. (3.7a), (3.7b), (3.7c), and (3.7d), the effective upper generation limits computed are summarised in Table 3.7.
Table 3.7 Effective upper generation limit

<table>
<thead>
<tr>
<th>Unit</th>
<th>(MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>450</td>
</tr>
<tr>
<td>4</td>
<td>450</td>
</tr>
</tbody>
</table>

The results obtained by the proposed evolutionary programming approach and $\lambda$-$\delta$ iterative method (Lee et al., 1993) are presented in Table 3.8.

Table 3.8 Unit power output levels with optimal fuel cost

<table>
<thead>
<tr>
<th></th>
<th>$P_1$(MW)</th>
<th>$P_2$(MW)</th>
<th>$P_3$(MW)</th>
<th>$P_4$(MW)</th>
<th>Fuel Cost ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP approach</td>
<td>350.00</td>
<td>360.00</td>
<td>332.53</td>
<td>332.47</td>
<td>16223.213</td>
</tr>
<tr>
<td>$\lambda$-$\delta$ iterative method</td>
<td>355.00</td>
<td>310.00</td>
<td>355.00</td>
<td>355.00</td>
<td>16224.175</td>
</tr>
</tbody>
</table>

Out of the two solutions provided by $\lambda$-$\delta$ iterative method, the second solution is not feasible because the generation level of the first unit is in its prohibited zone, thus violating constraint eqns. (3.6a), (3.6b), and (3.6c). Hence the results of the proposed method are compared in Table 3.8 with the first solution given in Lee et al (1993).

It is seen that the proposed approach yields almost the same fuel cost, but it automatically avoids generation levels falling into prohibited zones.
Example 3

This example system has five on-line units (Fan et al, 1994) represented by the following input-output functions:

\[
F_j(P_j) = 350 + 8 P_j + 0.001 P_j^2 + 1 \times 10^6 P_j^3 \text{ $/hr}$
\]

\[
120 \text{ MW} \leq P_j \leq 450 \text{ MW}, \quad j = 1, 2, 3, 4, 5
\]

Units 1, 2, and 3 have prohibited zones as defined in Table 3.9.

**Table 3.9 Unit prohibited zones**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Zone 1 (MW)</th>
<th>Zone 2 (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[240,275]</td>
<td>[315,375]</td>
</tr>
<tr>
<td>2</td>
<td>[210,270]</td>
<td>[300,390]</td>
</tr>
<tr>
<td>3</td>
<td>[200,250]</td>
<td>[290,370]</td>
</tr>
</tbody>
</table>

The system load demand \( P_D \) is 1175 MW.

Table 3.10 presents the results obtained by the proposed evolutionary programming approach and by the \( \lambda \)-\( \delta \) iterative method (Fan et al, 1994).

The population size considered for this example is large because of the larger permutation of generation outputs that satisfy the power balance constraint eqn. (3.3). Table 3.10 shows that the optimal cost obtained by the proposed
evolutionary programming approach is comparable to the result given in Fan et al (1994).

**Table 3.10 Unit power output levels and optimal fuel cost (Example 3)**

<table>
<thead>
<tr>
<th></th>
<th>$P_1$(MW)</th>
<th>$P_2$(MW)</th>
<th>$P_3$(MW)</th>
<th>$P_4$(MW)</th>
<th>$P_5$(MW)</th>
<th>Fuel Cost ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP approach</td>
<td>240.00</td>
<td>210.00</td>
<td>250.00</td>
<td>223.07</td>
<td>251.93</td>
<td>11493.23</td>
</tr>
<tr>
<td>$\lambda-\delta$ iterative method</td>
<td>238.33</td>
<td>210.00</td>
<td>250.00</td>
<td>238.33</td>
<td>238.33</td>
<td>11492.51</td>
</tr>
</tbody>
</table>

**Example 4**

This example considers the same system as in example 3 except that the system operates in a different environment, where each of units 4 and 5 is set to a fixed base generation level of 320 MW and is not dispatchable in real time. The system load demand $P_D$ is 1552 MW.

Table 3.11 presents the results obtained by the proposed evolutionary programming approach compared with the results obtained by the $\lambda-\delta$ iterative method in Fan et al (1994). Unlike in the previous examples where the optimal solutions are obtained in a single iteration, the optimal solution in this example is obtained in the second iteration only.
Table 3.11 Unit power output levels and optimal fuel cost (Example 4)

<table>
<thead>
<tr>
<th></th>
<th>P1(MW)</th>
<th>P2(MW)</th>
<th>P3(MW)</th>
<th>P4(MW)</th>
<th>P5(MW)</th>
<th>Fuel Cost ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP approach</td>
<td>375.0</td>
<td>270.0</td>
<td>267.0</td>
<td>320.0</td>
<td>320.0</td>
<td>14812.60</td>
</tr>
<tr>
<td>λ-δ iter. method</td>
<td>375.0</td>
<td>270.0</td>
<td>267.0</td>
<td>320.0</td>
<td>320.0</td>
<td>14812.62</td>
</tr>
</tbody>
</table>

Here too, the evolutionary programming approach yields the same results as compared to λ-δ iterative method.

Performance Analysis

From all these examples considered, it is observed that

- the population size and the number of constraints namely, the number of prohibited zones, ramp-rate limits and spinning reserve requirements are inversely related. As more and more constraints restrict the operating range of generating units, the feasible search area is reduced and a smaller population size is enough for a global search.

- The novel method of initialization and avoidance of generating infeasible solutions in the subsequent generations too, leads to convergence within a few generations with less population size and less computing time.
3.5 CONCLUSION

This chapter presented a new approach using evolutionary programming for solving economic dispatch problems when some or all of the units have prohibited operating zones. The versatility of the method in handling any number of constraints has also been shown by taking into account spinning reserve requirements and ramp-rate limits besides considering network losses. The proposed method has been tested on several problems and their results have been compared with those obtained by the traditional methods.