CHAPTER 3

CLUSTERING BASED UNIT COMMITMENT

3.1 Introduction

A new approach to the problem of large scale unit commitment is presented in this Chapter. The units are classified into various clusters based on their similarity of characteristics in order to reduce the computational time and also to satisfy the minimum up/down constraints easily. Unit commitment problem is an important optimizing task in daily operational planning of power systems which can be mathematically formulated as a large scale nonlinear mixed-integer minimization problem. A new methodology employing the concept of cluster algorithm called as additive and divisive hierarchical clustering has been employed along with particle swarm optimization in order to carry out the technique of unit commitment. Proposed methodology involves two individual algorithms. While the load is increasing, additive cluster algorithm has been employed and divisive cluster algorithm is used when the load is decreasing. The proposed technique is tested on a 10 unit system and the simulation results are analyzed in terms of performance as against the existing methods.

The Unit Commitment (UC) is an important research challenge and vital optimization task in the daily operational planning of modern power systems due to its combinatorial nature. Because the total load of the power system varies throughout the day and reaches a different peak value from one day to another, the electric utility has to decide in advance which generator to start up and when to connect them to the network and the sequence in which the operating units should be shut down and for how long. The computational procedure for making such decisions is called unit commitment, and a unit when scheduled for connection to the system is said to be committed. In this work the commitment of fossil-fuel units has been considered which have different production costs because of their dissimilar efficiencies, designs, and fuel types. Unit commitment plans for the best set of units to be available to supply the predict forecast load of the system over a future time period.
3.2.1 Unit’s Input-Output characteristic (Heat or Cost)

Unit (Boiler, turbine and generator) input-output curve establishes the relationship between energy input to the driving system and the net energy output from the generator. A typical boiler-turbine-generator unit is represented in Fig 3.1.

![Diagram of Boiler-Turbine-Generators Unit]

**Fig 3.1: Boiler -Turbine -Generators Unit**

In this characteristic the gross input ($/ hr or tons of coal/hr or millions of cubic feet of gas/hr or any other unit) being measured in millions of B.T.U. per hour (MBTU/hr) is plotted against the output in MW of the unit. The input is taken along y-axis. The output is normally the net electrical output of the unit and is taken along x-axis. Z-axis represent the time axis, on which usually one hour is taken to convert the output power P in MW to energy in MWhr in order to evaluate the per unit cost of input i.e., Plant is loaded at P (MW) for one hour, then input is measured in $ / hr or MBTU/h. (Z-axis can be omitted as each point loading pertains one hour).

The input-output characteristics of a steam unit in idealized form are represented in Fig 3.2.

![Diagram of Input-output Curve of a Steam Turbine Generator]

**Fig 3.2: Input-output Curve of a Steam Turbine Generator**
For a single value turbine the governing is done by throttling of steam and for such units, the input-output curve is substantially a straight line within its operating range.

3.2.2 Non convex fuel cost characteristic due to valve point effect

Non convex characteristic results due to valve point effect, multiple fuels and prohibited operating zones. The valve point effects produce a ripple, which is highly non-smooth and discontinuous as represented in Fig 3.3.

Fig 3.3: Input-output curve of a multi valve steam turbine generator with four steam admission valves

A= primary valve  B = secondary valve  C= Tertiary valve  D=Quaternary valve  E= Quinary valve

3.2.3 Incremental heat or cost characteristic

The incremental heat rate characteristic is the derivative of the input–output characteristic ($\Delta H/\Delta P$ or $\Delta F/\Delta P$). This characteristic is widely used in economic dispatching of units. It is converted to an incremental fuel cost characteristic by multiplying the incremental heat rate. The incremental heat rate characteristics for single and multi value units are represented in Figs 3.4 and 3.5 respectively. The incremental heat rate characteristic of multi valve steam turbine is discontinuous type.
Fig 3.4: Incremental Heat Rate or Cost characteristic

Fig 3.5: Incremental Heat Rate Characteristics of a steam turbine with four valves.

\[
\text{Incremental heat rate} = \frac{\Delta \text{Input}}{\Delta \text{Output}} = \frac{\Delta H}{\Delta P} \frac{\Delta F}{\Delta P}
\]

Fig 3.6: Heat rate and incremental heat rate curves for convex cost function

The heat rate and incremental heat rate can be converted into fuel cost function and incremental fuel cost by multiplying them with the cost of the fuel (Dollars per million of B.T.U.).
3.3 Formulation of Unit Commitment

Subject to the minimization of the cost-objective function in the unit commitment problem, certain units are stated to be as ‘ON’ and remaining as ‘OFF’. The following are the various notations considered during the implementation of the problem:

\[ N \] : Number of generating units in the plant;
\[ T \] : Scheduling period in hours (h);
\[ i \] : Index of Unit ( \( i = 1, 2, \ldots, N \));
\[ t \] : Index of time ( \( t = 1, 2, \ldots, T \));
\[ I_i(t) \] : \( i \)th unit status at \( t \)th hour;
\[ P_i(t) \] : Generation of \( i \)th unit at \( t \)th hour;
\[ p_i^{\text{num}} \] : Minimum output power (MW) of \( i \)th unit;
\[ p_i^{\text{max}} \] : Maximum output power (MW) of \( i \)th unit;
\[ D(t) \] : Demanded power at \( t \)th hour;
\[ R(t) \] : System reserve at \( t \)th hour;
\[ t_i^{\text{um}} \] : Minimum up time of \( i \)th unit;
\[ t_i^{\text{off}} \] : Minimum down time of \( i \)th unit;
\[ \chi_i^{\text{on}}(t) \] : Duration during which \( i \)th unit is continuously ON;
\[ \chi_i^{\text{off}} \] : Duration during which \( i \)th unit is continuously OFF;
\[ SC_i(t) \] : Start-Up cost of \( i \)th unit;
\[ FC_i(t) \] : Fuel cost of \( i \)th unit;
\[ TC \] : Total Cost of generation;
\[ HC(i) \] : Hot start cost of \( i \)th unit;
\[ CC(i) \] : Cold start cost of \( i \)th unit;
\[ CS(i) \] : Cold start hour of \( i \)th unit;
\[ a_i, b_i, c_i \] : Fuel cost coefficients in $/hr, $/MWhr, $/MW^2hr
3.3.1 Objective Functions

The objective function of UC problem is the minimization of the TC which has the components of FC and SC and is given by:

\[
\text{Min} \ (TC) = \sum_{i=1}^{N} \sum_{t=1}^{T} (FC_i(t) + SC_i(t))
\]  

(3.1)

Where Fuel cost of \( i \)-th unit:

\[
FC_i(t) = a_i + b_i P_i(t) + c_i P_i(t)^2
\]  

(3.2)

and Start-up cost

\[
SC_i(t) = HC(i) \cdot \begin{cases} 
T_i^{\text{on}} & \text{if } T_i^{\text{on}} \leq X_i^{\text{on}}(t) \leq H_i^{\text{on}}(t) \\
CC(i) & \text{if } X_i^{\text{on}}(t) < H_i^{\text{on}}(t)
\end{cases}
\]

(3.3)

where \( H_i^{\text{on}}(t) = T_i^{\text{on}} + CS(i) \cdot \text{Hot off cost of } i \)-th unit

3.3.2 System Constraints

The constraints, which must be considered during the optimization process of UC problem (1), are given below.

Load Demand

All the committed units must generate total power equal to load demand as:

\[
D(t) = \sum_{i=1}^{N} P_i(t)
\]  

(3.5)

3.3.3 Spinning Reserve

To maintain system reliability for sudden variation of loads, system should have adequate amount of spinning reserve capacity. In this paper 10\% of the load demand is taken and which satisfies:

\[
\sum_{i=1}^{N} I_i(t) \cdot P_i^{\text{max}} \geq D(t) + R(t)
\]  

(3.6)

Generated Power Limits
The power output of each unit should satisfy:

\[ p_{i_{\text{min}}} \leq p_i(t) \leq p_{i_{\text{max}}} \]  

(3.7)

Minimum Up/Down Time

Once the unit is committed there is a minimum time before it is de-committed and viz.

\[ T_{i_{\text{on}}} \leq X_{i_{\text{on}}}(t) \text{ or } T_{i_{\text{off}}} \leq X_{i_{\text{off}}}(t) \]  

(3.8)

3.4 Proposed Methodology

The purpose of Cluster Algorithms (CA) can be stated as, to divide a given group of objects into a number of groups or clusters in order that the objects in a particular cluster would be similar among the objects of the other ones. In the first stage of CA, an attempt is made to place an N object in M clusters according to some criterion additive to clusters. Once the criterion is selected, CA searches the space of all classifications and finds the one that satisfies the optimization function.

The proposed methodology for UC problem considers two clustering techniques: Additive Clustering Technique and Divisive Clustering Technique. In the first type of cluster technique, initially individual data points are treated as clusters. Based on some criteria (nearest operating costs of units) successively two closest clusters are merged until there is only one cluster remains.

**Basic Additive Clustering Algorithm**

**Step-1:** Compute operating cost (proximity) matrix;

**Step-2:** Repeat;

**Step-3:** Merge two closest clusters based on least distance value;

**Step-4:** Update the proximity Matrix to reflect the proximity between the new cluster and the original clusters;

**Step-5:** Until Only one cluster remains.
In the Divisive type clustering technique, successively each cluster is separated from the others until a singleton cluster of individual point(s) remain. A suitable methodology is required to take the decision on which cluster must be removed from the others. The basic algorithm is given below.

**Basic Divisive Clustering Algorithm**

**Step-1:** Compute operating cost (Proximity) Matrix;

**Step-2:** Repeat;

**Step-3:** Separate a cluster from other clusters based on maximum distance value;

**Step-4:** Update the proximity Matrix to reflect the proximity between the clusters those remaining;

**Step-5:** Until all the clusters are removed.

The flowchart for the above methodology can be observed from Fig 3.7

![Flowchart](image_url)

*Fig 3.7: Methodology of additive and divisive cluster algorithm*
The proposed methodology can be unfolded into three stages.

- In this stage, the objective cost function of each unit is obtained by using genetic algorithm. Priority list of units is prepared based on the minimum objective cost functions and clusters are formed.

  The pattern of load variation on the plant is a cycle of increasing and then decreasing. Two separate algorithms are designed for load increasing pattern and for decreasing pattern. In this stage, an algorithm based on agglomerative clustering technique is developed for increasing load pattern.

- This stage presents an algorithm for UC solution for the decreasing load condition. The algorithm is designed based on divisive clustering technique.

  The operating cost of each plant is calculated and the units are clustered based on their objective function values. In this way, best clusters are brought out so that they can be employed to take up the load.

3.5 Characterization of the Units

Base load (BL) and Intermittent load (IL) units operate for long period in the day and they generate more number of units (MWH). Therefore, ideally speaking they should have minimum fuel cost, maximum generating capabilities but, can have high start-up costs and start-up times for the reason they are switched ‘on’ for the most of time. In addition, System reliability aspect is decided by the performance of these units. Semi-Peak Load (SPL) and Peak load (PL) units in contrast should have low start-up costs and start-up times as these units are rapidly switched ‘ON’ and ‘OFF’ frequently. These units can have less generating capabilities and can have relatively high costs as they take up small loads above high base load and intermittent loads. Based on the generation cost functions, the closet cost function units are segregated into clusters as BL, IL, SPL and PL as given in table 5.

BL : Load up to 1000MW duration: 0-24 hours

IL : Load between 1000MW to 1200 MW, duration 0-18 hours

SPL: Load 1200MW to 1400 MW, duration 0-6 hours
PL : Load 1400MW to 1500MW, duration 0-3 hours

The maximum limits for the four loads as:

BL-Max: 1000 MW; IL-Max: 1200 MW; SPL-Max: 1400 Mw and PL-Max: 1500 MW.

For carrying out the additive cluster algorithm, objective function values are stored in ascending order and for divisive cluster algorithm the objective function values are stored in the descending order as given in table 4. The closest values are divided into four clusters as BL, PL, Semi PL and IL.

**Design of Additive Clustering (AC) Algorithm for UC Problem**

Flow chart of AC and DC algorithm for UC problem is shown in Fig.3.7

**AC Algorithm:**

**Step-1:** Read the load value $D(t)$, Spinning Reserve requirement $R(t)$. Threshold values of four clusters.

**Step-2:** From the load duration curve, identify the load as any: BL, IL, SPL or PL.

**Step-3:** Commit the units in corresponding cluster by executing subroutine for Economic Dispatch (ED).

**Step-4:** Check the constraint: $D(t) + R(t) < \text{Cluster Threshold value}$. If condition is satisfied, go to main program. Else, go to next step.

**Step-5:** Merge next priority list cluster to previous cluster.

**Step-6:** Go to Step-4;

**Step-7:** Return

The subroutine for ED is standard Lambda-Iteration Method. The ED has following steps.
**ED by Lambda-Iteration Method:**

**Step-1:** Set $\lambda$ value.

**Step-2:** Calculate $P_i$ for $i = 1, 2 \ldots n$. Where $n$ is the number of units in the cluster. $P_i$ is calculated subject to the minimization of objective function (3.1) under the constraints (3.5)-(3.8).

**Step-3:** Calculate error $\epsilon$ value (difference between demanded load and sum of generations).

**Step-4:** Check $\epsilon$ with tolerance value. If yes Go to main program to print UC results. Else set new value of $\lambda$. Go To Step-2.

**Design of Divisive Clustering (DC) Algorithm for UC Problem**

This DC algorithm is proposed for UC when the load is decreasing after it stopped from increasing. The DCA starts at the point where some units in various clusters are already under 'on' condition. Now the requirement is to put some units under 'off' condition, so as to meet the present $D(t)$. The priority list is prepared based on the start-up time/costs. The strategy is, to put off the unit with maximum generation cost.

**DC Algorithm:**

**Step-1:** Read the system load.

**Step-2:** De-Commit the next unit with maximum generation cost according to priority list.

**Step-3:** Commit the units in corresponding cluster by executing subroutine for Economic Dispatch (ED).

**Step-4:** Check the constraint: $D(t)+R(t) \leq$ sum of all generations. If condition is satisfied, go to main program. Else, go to step-2.

**Step-5:** Return.
3.6 Results and Discussions

Table 3.1 shows the daily load pattern on the plant and Table 3.2 shows the operating characteristics of all the units [38].

<table>
<thead>
<tr>
<th>Table 3.1: Daily Load Pattern on the Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hour</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>
Table 3.2: Operational characteristics of all units

<table>
<thead>
<tr>
<th>Unit No. (i)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{max}}$ (MW)</td>
<td>455</td>
<td>455</td>
<td>162</td>
<td>130</td>
<td>130</td>
<td>80</td>
<td>85</td>
<td>55</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>$P_{\text{min}}$ (MW)</td>
<td>150</td>
<td>150</td>
<td>25</td>
<td>20</td>
<td>20</td>
<td>25</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$a_i$ (hr)</td>
<td>1000</td>
<td>970</td>
<td>450</td>
<td>680</td>
<td>700</td>
<td>370</td>
<td>480</td>
<td>660</td>
<td>665</td>
<td>670</td>
</tr>
<tr>
<td>$b_i$ (kWh/Wh)</td>
<td>16.19</td>
<td>17.26</td>
<td>19.7</td>
<td>16.5</td>
<td>16.6</td>
<td>22.26</td>
<td>27.74</td>
<td>25.92</td>
<td>27.27</td>
<td>27.79</td>
</tr>
<tr>
<td>$c_i$ ($/\text{kWh}$)</td>
<td>0.00048</td>
<td>0.00031</td>
<td>0.00398</td>
<td>0.00211</td>
<td>0.002</td>
<td>0.00712</td>
<td>0.00079</td>
<td>0.00413</td>
<td>0.00222</td>
<td>0.00173</td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$T_{\text{max}}$</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$HC(i)$ ($/L$)</td>
<td>4500</td>
<td>5000</td>
<td>900</td>
<td>560</td>
<td>550</td>
<td>170</td>
<td>260</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>$CC(i)$ ($/L$)</td>
<td>9000</td>
<td>10000</td>
<td>1800</td>
<td>1120</td>
<td>1100</td>
<td>340</td>
<td>520</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$CS(i)$</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\text{Init. State}$</td>
<td>8</td>
<td>8</td>
<td>-6</td>
<td>-5</td>
<td>-5</td>
<td>-3</td>
<td>-3</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
</tbody>
</table>

The average fuel costs and start up costs for all the units can be calculated as follows:

$$A = \text{Average fuel cost of system} = \frac{a_i + b_i P_{\text{max}} + c_i P_{\text{max}}^2}{P_{\text{max}}}$$

$$B = \text{Average start up cost} = \frac{HC(i)}{P_{\text{max}}}$$

The Euclidian costs of all the units can be calculated as follows:

$$\text{Euclidian costs of the unit} = \sqrt{(A_i - A_{\text{low}})^2 + (B_i - B_{\text{max}})^2}$$

The above calculations of all the units have been tabulated in Table 3.3 and Table 3.4 respectively.
Table 3.3: Average fuel cost and start up cost of each unit

<table>
<thead>
<tr>
<th>Unit No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>18.606</td>
<td>19.533</td>
<td>23.123</td>
<td>22.005</td>
<td>22.245</td>
<td>27.455</td>
<td>33.454</td>
<td>38.147</td>
<td>39.483</td>
<td>40.067</td>
</tr>
<tr>
<td>B</td>
<td>9.8901</td>
<td>10.989</td>
<td>5.5556</td>
<td>4.3077</td>
<td>4.2308</td>
<td>2.125</td>
<td>3.0588</td>
<td>0.54545</td>
<td>0.54545</td>
<td>9.8901</td>
</tr>
</tbody>
</table>

Table 3.4: Euclidian cost of all units

<table>
<thead>
<tr>
<th>Unit No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euclidian cost</td>
<td>1.0989</td>
<td>0.92672</td>
<td>7.0654</td>
<td>7.4962</td>
<td>7.6754</td>
<td>12.525</td>
<td>16.833</td>
<td>22.157</td>
<td>23.343</td>
<td>23.867</td>
</tr>
</tbody>
</table>

Table 3.5 shows the priority order of various units corresponding to their Euclidian costs with respect to additive clustering and divisive clustering and Table 3.6 shows the segregation of all the 10 units in order to take up the daily load pattern.

Table 3.5: Priority list is formed with minimum operation cost

<table>
<thead>
<tr>
<th>Priority Order</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>For ACA</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>For DCA</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.6: Segregation of 10 units into clusters and their priority

<table>
<thead>
<tr>
<th>Cluster type</th>
<th>Base load</th>
<th>Intermittent load</th>
<th>Semi peak load</th>
<th>Peak load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority units in</td>
<td>1,2</td>
<td>3,4,5</td>
<td>6,7</td>
<td>8,9,10</td>
</tr>
</tbody>
</table>

Table 3.7 shows the allocation of generation to various units based on the daily load pattern and based on the clusters. It can be observed from the table that the clusters only take up the load allotted to them while the other generators do not take up the load until it falls into the other category. The operating costs of the generators taking the load can be observed from the table. It can be observed that the technique is quite simple and also the convergence time is also very less as compared to other techniques.
Table 3.7: Generation of units in 24 hour schedule

<table>
<thead>
<tr>
<th>S.No</th>
<th>Load (MW)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>700</td>
<td>342.4</td>
<td>357.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>750</td>
<td>362.0</td>
<td>387.9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>850</td>
<td>370</td>
<td>159</td>
<td>162</td>
<td>130</td>
<td>29</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>950</td>
<td>455</td>
<td>159</td>
<td>162</td>
<td>130</td>
<td>44</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>1000</td>
<td>334.1</td>
<td>344.8</td>
<td>162</td>
<td>130</td>
<td>29</td>
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<td>0</td>
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</tr>
<tr>
<td>6</td>
<td>1100</td>
<td>373.40</td>
<td>405.5</td>
<td>162</td>
<td>130</td>
<td>29</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
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Total Operating cost 584325
3.7 Conclusions

A novel method based on clustering technique is proposed to mitigate Unit Commitment problem. The proposed method is more realistic and less heuristic. Following load pattern, two individual algorithms based on Additive and Divisive cluster algorithms are proposed for increasing and decreasing load patterns. The Euclidian cost of generation of units is obtained and based on these costs the units are segregated into clusters. Two separate priorities lists one for increasing and another for decreasing load conditions are prepared based on generation costs. A 10-thermal unit system is considered for simulation study. The strategy employed proved to be quite effective and satisfactory as evident from simulation results.