The Application of Fuzzy Theory to Thermal Generating Unit Maintenance Scheduling in Power Systems

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Fuzzy theory has been applied to the thermal power station generating unit maintenance scheduling problem to devise a new method where inherent uncertainty elements are represented appropriately. More specifically, this method uses fuzzy membership functions to represent load demand and supply reserve capacity for each given time interval within the maintenance period and the future years, respectively. The Branch and Bound method is used for the optimisation search.

The basic objective is to equalise the supply reserve capacity using fuzzy membership functions for load demand in the maintenance period, thereby obtaining an averaged value which contains the load’s degree of uncertainty. In addition, membership functions for load and reserve capacity are used to check future year reserve capacity levels to ensure that a given scheduling solution will allow future feasible solutions. To test the effectiveness of this method, simulations were run in tandem with a previously developed method which deals with load reserve capacity values deterministically. For the purpose of comparison, this deterministic approach is also briefly outlined in this paper. The results of these simulations are given in the Numerical Examples section.

Key words: Power systems, Maintenance scheduling, Fuzzy theory, Branch and Bound method

1. Introduction

Thermal power station unit maintenance scheduling has to be determined carefully taking into account such aspects as reliability and economy\(^{(1)-(3)}\). It has become a particularly important power system operation planning problem because of ever decreasing natural resources and growing load demand. Conventionally, the scheduling method is based on the deterministic equalisation of the supply reserve capacity for the maintenance period while considering multi-year constraints\(^{(4)}\). The term deterministic means that uncertainty elements, e.g., load demand and supply reserve capacity, are dealt with as crisp or discrete values. However, most external factors influencing these elements such as climatic conditions and consumer demands contain uncertainty, or fuzziness, and increase with time. Thus, it is desirable to represent or deal with these fuzzy elements appropriately in order to devise a more flexible and realistic maintenance plan reflecting human subjectivity. Here, flexibility addresses three areas. Firstly, in that the operator can be flexible in dealing with load forecasting information. Secondly, having flexibility for dealing with operator intentions in terms of the reserve capacity constraint. Thirdly, having flexibility in being able to obtain solutions when stringent constraints are applied. Of these three, only the third can be illustrated by numerical analysis. One such method that attempts to reflect human subjectivity and flexibility is the approach in Ref. \((4)\) which fuzzifies objectives (reserve capacity and production cost) and constraints (manpower, maintenance window and geographical), giving all functions upper and lower limits. This approach also uses dynamic programming, however, this cannot be successfully applied to the maintenance scheduling problem and therefore appears to be a major oversight.

However, this paper presents a new approach which applies fuzzy functions to express external elements of uncertainty beyond operation control, i.e., load and supply reserve capacity, and does not compromise
constraint settings. This proposed method of applying fuzzy theory is based on the algorithm of the deterministic method in that its main objective is to equalise the reserve capacity while considering multi-year constraints and also uses the Branch and Bound method for optimisation. However, the proposed method differs from the deterministic method because equalisation of an averaged reserve capacity value containing the degree of uncertainty of load is achieved by the application of membership functions to represent load demand for the maintenance period. In addition, simplified membership functions are used to represent load and reserve capacity for the immediate following years in order to carry out future-year constraint checks with regards to future reserve capacity levels. Therefore, it is possible to obtain a more flexible maintenance scheduling approach when compared to the deterministic approach. This is partly because in the deterministic method, the future reserve capacity constraint check considers the margin between crisp, or discrete load values and the pre-nominated minimum reserve capacity constraint value. In contrast, the proposed method evaluates the common area between load and reserve capacity. Therefore, this method allows human subjectivity for expressing suitable load and reserve capacity ranges and for selecting suitable index values to check future year capacity levels.

An investigation of the proposed method's effectiveness is carried out by comparing its performance with that of the deterministic method.

2. Maintenance scheduling by equalisation

2.1 Basic problem formulation

To ensure power system supply reliability it is necessary to have regular maintenance inspections for each generating unit in the system. For this reason, one of the conventional objectives of maintenance scheduling is equalisation of the reserve capacity over the maintenance period. This is done in order to maintain sufficient supply capacity at all times. In addition, various constraints have to be considered for reasons of reliability and also because most power supply authorities have limited labour resources due to the necessity to relocate manpower to the various stations in the system. In this paper, the constraints are considered in two parts:

(1) pre-branching constraints.
(2) post-branching constraints.

(1) The pre-branching constraints are checked for the current unit prior to determining the optimal branching option (maintenance inspection time) from results of the equalisation objective function calculations. For each possible maintenance time interval, all constraints have to be satisfied otherwise the interval is marked as infeasible for the current unit. The pre-branching constraints are as follows:

(i) Due to manpower limitations, the station locations are classified into coastal siting or inland siting. No more than 2 coastal units can undergo maintenance inspections simultaneously. In addition, only 1 inland unit can undergo a maintenance inspection during any given time interval.

(ii) Again due to manpower limitations, only 1 unit in any one station can undergo a maintenance inspection during any given time interval.

(iii) Minimum reserve capacity: for all possible maintenance time intervals, a check is made to ensure that this constraint is not violated. It is a check of the margin between the effective supply capacity and the expected load level.

(2) Post-branching constraints

In brief, after provisionally determining a given unit's maintenance inspection time, it is necessary to ensure that the solution (schedule) allows solutions for that unit in the following maintenance periods (future years). For this, the most important consideration is the supply reserve capacity. Therefore, possible future solutions for the given unit are determined and the reserve capacity level in each time interval is checked. If this constraint is violated it is necessary to return to the unit's next best branching option and repeat this constraint check, otherwise backtrack and adjust the solutions of previous units.

2.2 Optimisation using discrete values

In Ref. (1), the objective function for equalising the supply reserve capacity rate over the maintenance period is defined by Eq. (1).

\[ f = \sum_{i=1}^{n} (R_{max} - R_i)^2 \]  

(1)

\( R_{max} \) is the initial maximum reserve capacity rate and is determined prior to the actual scheduling process by comparing the total supply capacity and load demand in each time interval of the maintenance period, making it a reference value for the equalisation formula to ensure that troughs in the load curve (time intervals with high reserve capacity levels) are given preference for the scheduling of maintenance. \( R_i \) is the reserve capacity rate during time interval \( i \), and \( I_{max} \) represents the maintenance period, in the case of this research this is 1 year, and is divided into 36 time intervals.

An example load curve shown in Fig.1 illustrates
these parameters graphically.

The Branch and Bound method (depth preferential approach) is applied for optimisation purposes and is shown in a later section in Fig. 5. This technique is most suitable for the scheduling problem because the individual generating units in the system are given a ranking order and each unit generally has various maintenance time interval options with constraint considerations, therefore the problem can be solved using an enumeration tree type approach. This technique also allowsbacktracking which is necessary when constraints cannot be satisfied.

Because the Branch and Bound algorithm is applicable to both the proposed and the deterministic methods it will be described in Section 3.4.

The definition of an optimal solution, is the solution with the best equalised reserve capacity that satisfies all constraints.

3. Application of fuzzy theory

3.1 Definition of membership function

In the deterministic approach as briefly outlined above, the factors pertaining to future load and supply capacity levels are handled discretely, however, a degree of uncertainty exists. In order to appropriately express this uncertainty, we can for example, consider the membership function in Fig. 2 as a representation of load demand. The reason for choosing a fuzzy function to represent load is that probability theory cannot be applied to express this uncertainty. This is because load forecasting information usually provides the operator with a discrete value for each time interval, however, we know the actual value will differ slightly but it is very difficult to apply probability curves as the exact range and weighting in each part of this range is not known. Thus, it is necessary to provide an approach that allows the operator to roughly define a range which he thinks appropriate. Further, unlike probability theory, with fuzzy theory different operators will provide different answers, hence the inclusion of subjectivity.

The range of the membership function in Fig. 2 is defined by 4 parameters, $P_{\text{min} 0}$, $P_{\text{min} 1}$, $P_{\text{max} 1}$ and $P_{\text{max} 0}$. The range from $P_{\text{min} 1}$ to $P_{\text{max} 1}$ is where we expect the load to most likely be $\mu_L(P_i) = 1$, and the outer range defined by $P_{\text{min} 0}$ and $P_{\text{max} 0}$ indicates a reduced degree of expectation. Linear equations, as shown, express the value of the membership function for the 2 outer sloping regions. Other constraints or governing elements can be defined by membership functions in similar fashion, however, for simplicity in this paper we only consider load as the element containing uncertainty for the maintenance period.

Using this concept of load uncertainty, it is therefore necessary to extend the previous objective function in order to carry out minimisation and also by a separate calculation technique check the future-year reserve capacity of the resulting scheduling solution.

3.2 Relevant year objective function

Taking into account the uncertainty of the load from Fig. 2 results in the objective function for the relevant year (maintenance period) as defined by Eq. (2).

$$f = \sum \int (R_{\text{max}} - R(P_i)) \mu_L(P_i) dP_i.$$

From this it can be seen that the basic minimisation function has remained intact, however, the membership function value, $\mu_L(P_i)$, is now included. This means that the objective function when derived contains the integration of the area under the load membership function, such that the value obtained will be an averaged value containing the degree of uncertainty of the load. The next step is to break this objective function equation down into parts so that load values can be substituted into the equation, hence it becomes the following for a given time interval:

$$f_a = \int_{P_{\text{min} 1}}^{P_{\text{max} 1}} (R_{\text{max}} - (P_{\text{min} 1} - P_i))^2 (aP_i + \beta) dP_i.$$

From this it can be seen that the basic minimisation function has remained intact, however, the membership function value, $\mu_L(P_i)$, is now included. This means that the objective function when derived contains the integration of the area under the load membership function, such that the value obtained will be an averaged value containing the degree of uncertainty of the load. The next step is to break this objective function equation down into parts so that load values can be substituted into the equation, hence it becomes the following for a given time interval:

$$f_a = \int_{P_{\text{min} 1}}^{P_{\text{max} 1}} (R_{\text{max}} - (P_{\text{min} 1} - P_i))^2 (aP_i + \beta) dP_i.$$

$$f_b = \int_{P_{\text{max} 1}}^{P_{\text{max} 0}} (R_{\text{max}} - (P_{\text{max} 1} - P_i))^2 dP_i.$$

$$f_c = \int_{P_{\text{min} 0}}^{P_{\text{min} 1}} (R_{\text{max}} - (P_{\text{min} 0} - P_i))^2 (\gamma P_i + \delta) dP_i.$$
the boundaries of the membership function. \( R_i \) and \( R_{\text{max}} \) are equivalent to the variables in Eq. (1), however, here they are not the rates of reserve capacity, instead actual values of reserve capacity. \( R_i \) equals \( P_g \) minus \( P_i \) where \( P_i \) is substituted with the boundary points for each of the 3 integration equations. Parameters \( \alpha, \beta, \gamma \) and \( \delta \) are calculated geometrically from membership function point values. \( R_{\text{max}} \) is now the maximum reserve capacity considered possible during the maintenance period. In other words, the margin between the total supply capacity, \( P_g \), and the membership function’s smallest parameter (\( P_{\text{min}} \)) for the time interval with the largest reserve capacity.

Fundamentally, even though the objective of this function is also to equalise (minimisation process) the reserve capacity, constraints must be simultaneously checked and satisfied at all times. Again, when looking at the maintenance period, as the respective unit’s maintenance times are successively determined, the objective function value, \( f \), increases. Therefore, to search for an optimal maintenance scheduling solution, the application of the Branch and Bound method (refer to Fig. 5) is again appropriate.

3.3 Future-year evaluation index

In order to check the feasibility of future maintenance scheduling with respect to supply reserve capacity levels the membership function as shown in Fig. 3 was established. \( \mu S(R_i) \) is the reserve capacity membership function value which expresses the operator’s degree of satisfaction with respect to supply reserve capacity. This function is defined by 2 parameters, \( R_1 \), a reserve capacity level that completely satisfies operator intentions and, \( R_0 \), the lowest acceptable reserve capacity level. As noted in Section 3.1, for the maintenance period only load is considered as the element containing uncertainty for simplicity, thus it can be said that we have assumed that the theoretical reserve capacity membership function during the maintenance period has only 1 parameter, \( R_1 \), making it unnecessary to include in calculations.

Next, to make use of this future year reserve capacity function, we have defined an evaluation index as follows.

\[
IM = \frac{\int \mu S(P_i) \mu L(P_i) dP_i}{\int \mu L(P_i) dP_i}
\]  

(6)

The resultant, \( IM \), is used as an evaluation index to check the supply reserve capacity level. \( \mu S(P_i) \) becomes the reserve capacity membership function value taken with respect to load and \( \mu L(P_i) \) is the load membership function value. This formula is used for individual time intervals in the future maintenance periods (i.e., 2nd, 3rd and 4th years).

From this we can establish constraint values for each future year in order to apply the index. Further, the easing of constraints through consecutive future years is possible because we may assume that the uncertainty of the load and reserve capacity increases. It is important to realise that the future year reserve capacity check does not have to be performed as rigidly as that for the maintenance year, therefore if the above index settings are such that no feasible solution is obtainable, then it may be acceptable and appropriate to adjust their values.

Fig. 4 shows the resulting function relating to the supply reserve capacity’s degree of satisfaction and that of the load’s degree of uncertainty when plotted together. Note that \( R_1 \) and \( R_0 \) are subtracted from the supply capacity, \( P_g \), for graphical parity. The sloping section of the reserve capacity function (from \( P_g - R_1 \) to \( P_g - R_0 \)) is defined by the linear equation as given in the figure. \( \gamma \) and \( \delta \) are calculated geometrically from membership function point values. For simplicity we have assumed a rectangular function for the load which is defined by 2 parameters, \( P_{\text{max}} \) and \( P_{\text{min}} \). For example, in this case where the load function parameters both lie within the sloping region of the reserve capacity function, using the generalised evaluation index function (Eq. (6)) results in the following.

\[
IM = \delta + \gamma P_o - \gamma (P_{\text{max}} + P_{\text{min}})/2
\]

(7)

From the shapes of the 2 membership functions in Fig. 4
it can be clearly understood that 6 configurations are possible, hence 6 evaluation index functions. Naturally, if $P_{\text{max}}$ is less than or equal to $P_{\text{R}}$, then we can assume that the reserve capacity level is completely satisfactory as we can consider there to be minimal chance of the reserve capacity level being inadequate. Conversely, if $P_{\text{min}}$ is greater than or equal to $P_{\text{R}}$, then the reserve capacity level is completely unsatisfactory.

### 3.4 Optimisation algorithm

The optimisation search technique is the Branch and Bound method as shown in Fig. 5. The essential differences between the proposed method and the deterministic method are, (i) the formulation of the objective function for equalising the maintenance period reserve capacity, and (ii), the application of membership functions and the devising of the evaluation index to check future year reserve capacity levels. The following is a brief explanation of the various steps of the algorithm. Note that this algorithm is also applicable to the deterministic method.

(Step 1) Set generating unit number (NG) to 0.

(Step 2) Set provisional ceiling value (Z) to a high number (infinity), initially this can be set to an arbitrarily high number considered to be a relative infinity to ensure that only valid scheduling solutions are obtained. This ceiling value is the basis for the operating limit and although it is set initially to relative infinity, it becomes the aggregated objective function value, $f$, when the last unit is initially reached, in this way the current solution becomes the operating limit so that any solutions obtained from this point become successively more optimal. Refer to Step 5.

(Step 3) Enter next generating unit (initially NG = 1), i.e., after the current unit has been provisionally scheduled for a maintenance outage the next unit in the ranking order is considered.

(Step 4) Determine all possible maintenance periods for the current unit. This process is referred to as branching and is carried out by using the unit’s historical data. From this data there is an earliest possible maintenance start time and a latest possible start time so between these, various ‘branches’ are available and checked against manpower and minimum reserve capacity constraints. Next, calculate the objective function value (proposed method: Eq. (2), deterministic method: Eq. (1)), and select the branch which produces the lowest objective function value.

(Step 5) Compare the objective function value with that of the provisional ceiling value. If it is less than the provisional value continue to the next step, otherwise backtrack i.e., go to the previous generating unit, select its next best branching option and repeat provisional value comparison check.

(Step 6) Check future-year constraints by using the evaluation index. If future-year constraints are not satisfied, go to the next best branching option for the current unit and return to Step 5, otherwise go to next step.

(Step 7) Go to next unit in the ranking order (i.e., return to step number 3). After the until last unit has been completed, set the provisional ceiling value to current objective function value and backtrack until returning to the first unit to search for a further optimised solution.

### 4. Numerical examples

#### 4.1 Test system

To assess the effectiveness of the proposed method a comparison was made simultaneously with the deterministic method using the same initial load and unit data. In brief, the test system comprises of 16 thermal generating units from 11 different stations with a total combined output capacity of 3,182 MW. Table 1 gives generating unit data and Table 2 gives load input data which is used for both the maintenance period and also the future years. Other types of units in the system are only considered quantitatively, these being 2 nuclear powered units with a combined capacity of approximately 1,000 MW and other units such as hydroelectric units which supply on average approximately 1,000 MW.
Table 1. Generating unit input data.

<table>
<thead>
<tr>
<th>Unit name</th>
<th>Thermal unit capacity (MW)</th>
<th>First possible start time</th>
<th>Last possible start time</th>
<th>Maintenance time required</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>121</td>
<td>33</td>
<td>33</td>
<td>3</td>
<td>S</td>
</tr>
<tr>
<td>B</td>
<td>70</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>S</td>
</tr>
<tr>
<td>C</td>
<td>117</td>
<td>33</td>
<td>33</td>
<td>3</td>
<td>L</td>
</tr>
<tr>
<td>D-1</td>
<td>117</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>L</td>
</tr>
<tr>
<td>D-2</td>
<td>117</td>
<td>23</td>
<td>25</td>
<td>3</td>
<td>L</td>
</tr>
<tr>
<td>E-1</td>
<td>163</td>
<td>12</td>
<td>14</td>
<td>3</td>
<td>L</td>
</tr>
<tr>
<td>E-2</td>
<td>163</td>
<td>34</td>
<td>36</td>
<td>3</td>
<td>L</td>
</tr>
<tr>
<td>F-1</td>
<td>326</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>S</td>
</tr>
<tr>
<td>F-2</td>
<td>358</td>
<td>17</td>
<td>19</td>
<td>3</td>
<td>S</td>
</tr>
<tr>
<td>G</td>
<td>243</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>S</td>
</tr>
<tr>
<td>H-1</td>
<td>340</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td>S</td>
</tr>
<tr>
<td>H-2</td>
<td>340</td>
<td>15</td>
<td>16</td>
<td>3</td>
<td>S</td>
</tr>
<tr>
<td>I</td>
<td>340</td>
<td>30</td>
<td>31</td>
<td>3</td>
<td>S</td>
</tr>
<tr>
<td>J-1</td>
<td>74</td>
<td>21</td>
<td>23</td>
<td>6</td>
<td>S</td>
</tr>
<tr>
<td>J-2</td>
<td>74</td>
<td>11</td>
<td>13</td>
<td>6</td>
<td>S</td>
</tr>
<tr>
<td>K</td>
<td>19</td>
<td>10</td>
<td>12</td>
<td>3</td>
<td>S</td>
</tr>
</tbody>
</table>

Table 2. Load and other unit input data.

<table>
<thead>
<tr>
<th>Time interval (Apr. to Sept.)</th>
<th>System demand (MW)</th>
<th>Output from other unit types (MW)</th>
<th>Time interval (Oct. to Mar.)</th>
<th>System demand (MW)</th>
<th>Output from other unit types (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3 (April)</td>
<td>3,590</td>
<td>833</td>
<td>19-21 (Oct)</td>
<td>4,150</td>
<td>1,067</td>
</tr>
<tr>
<td>4-6 (May)</td>
<td>3,670</td>
<td>1,131</td>
<td>22-24 (Nov)</td>
<td>4,255</td>
<td>1,073</td>
</tr>
<tr>
<td>7-9 (June)</td>
<td>3,845</td>
<td>1,167</td>
<td>25-27 (Dec)</td>
<td>4,305</td>
<td>1,063</td>
</tr>
<tr>
<td>10-12 (Jul)</td>
<td>4,010</td>
<td>1,057</td>
<td>28-30 (Aug)</td>
<td>4,210</td>
<td>893</td>
</tr>
<tr>
<td>13-15 (Aug)</td>
<td>4,030</td>
<td>1,076</td>
<td>31-33 (Feb)</td>
<td>4,160</td>
<td>861</td>
</tr>
<tr>
<td>16-18 (Sep)</td>
<td>4,010</td>
<td>1,069</td>
<td>34-36 (Mar)</td>
<td>3,945</td>
<td>822</td>
</tr>
</tbody>
</table>

depending on unit commitment schedules (Table 2). In brief, the given generating unit data consists of the ranking number, generating output capacity, historical maintenance data and station location.

The historical maintenance data includes the first and last possible start times available for the next maintenance inspection (i.e., branching options), and also the type of inspection required (complete, semi-complete or simple inspection).

To carry out the simulations it was necessary to formulate some simple membership function parameter selection guidelines. The given data containing uncertainty was chiefly the forecasted load value corresponding to each time interval in the maintenance and following (future) years. We have assumed this value to basically be a maximum. Note that in practice the forecasting accuracy over a year period is typically between 2% and 3% with respect to the actual load incurred. From the membership function shown in Fig. 2 there are 3 regions to consider in which we have

assumed that the sloping region from \( P_{\text{max}1} \) to \( P_{\text{max}0} \) has the smallest margin because the forecasted value \( P_{\text{max}1} \) is assumed to be pessimistically large. Therefore, the remaining 2 regions (from \( P_{\text{min}0} \) to \( P_{\text{max}1} \)) are considered to be larger because load occurrence below \( P_{\text{max}1} \) is more probable (Fig. 2 is not drawn to scale). Note that \( P_{\text{max}1} \) is set at the deterministically forecasted value given.

For the future-year constraint check the shape of the load's membership function is taken as being rectangular for simplicity. Therefore, it has only 2 parameters, the maximum being set around the forecasted value in a proportioned manner with a similar setting policy to that for the maintenance period where the load expectancy is greater below the forecasted value. The parameters of the reserve capacity membership function, \( R_i \) and \( R_o \), have been set with a margin of 0.5%, with \( R_i \) being set at the value that corresponds to the current minimum reserve capacity constraint setting for the maintenance period.

Table 3 gives the membership function parameter settings used for the results given in this paper. As shown, 2 different sets of values were used for the evaluation index, \( IM \), with a general policy that the level of severity decreases with time (yearly) because it can be assumed that other external factors such as increased system capacity may be considered. In addition to this assumption, it must be realised that this is only a secondary check which does not directly affect the operation of the system for the maintenance period.

Note that the programme was written using Fortran

Table 3. Simulation parameter settings.

<table>
<thead>
<tr>
<th>PARAMETER SETTING</th>
<th>PMIN</th>
<th>PMAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUZZY BAND MAINTENANCE YEAR (%)</td>
<td>94</td>
<td>100</td>
</tr>
<tr>
<td>FUTURE BAND (%)</td>
<td>94.5</td>
<td>103.5</td>
</tr>
<tr>
<td>IM(=A)</td>
<td>YEAR 2 = 0.90</td>
<td>YEAR 3 = 0.80</td>
</tr>
<tr>
<td>IM(=B)</td>
<td>YEAR 2 = 0.96</td>
<td>YEAR 4 = 0.70</td>
</tr>
</tbody>
</table>

Table 4. Comparison of proposed method(1) vs. deterministic method(2).

<table>
<thead>
<tr>
<th>REMIN (%)</th>
<th>NUMBER OF SOLUTION</th>
<th>COMPUTATION TIME (MIN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUZZY (A)</td>
<td>FUZZY (B)</td>
<td>NON FUZZY</td>
</tr>
<tr>
<td>7.5</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>12.5</td>
<td>7</td>
<td>16</td>
</tr>
</tbody>
</table>

1. Proposed method equals fuzzy method.
2. Deterministic method equals non-fuzzy method.
4.2 Results of optimisation

The first numerical results are shown in Table 4. Three sets of results are shown, i.e., Fuzzy 'A' (proposed method for $IM = A$), Fuzzy 'B' (for $IM = B$) and Non-fuzzy (deterministic method). Three values for $RR_{min}$, the minimum reserve capacity constraint level, were used. For the proposed method this is the margin from $P_t$ to $P_{max}$.

The membership function parameter settings are as per Table 3. The results show the number of solution iterations as well as computation time. The 'number of solution iterations' refers to the total number of iterations required before the optimal solution is reached. For example, at $RR_{min}=7.5\%$ Fuzzy 'A' required 6 solution iterations, Fuzzy 'B' 15 and Non-fuzzy 7. The first iteration (solution) is obtained when $NG=NG_{max}$ (refer to Fig. 5) and the final solution (i.e. Fuzzy 'A'= 6) is the optimal solution.

For all 3 $RR_{min}$ settings the number of iterations of the methods varies considerably depending on what solution search paths are taken and also a characteristic of the branch and bound process. Of significance is that the Fuzzy approach generally requires longer computation time, because of the long integration calculations required with the objective function and the evaluation index. This difference in computation time decreases as $RR_{min}$ increases because there are less branching options available due the future year constraints not being satisfied.

From the actual schedules obtained for the proposed method, a deterministic calculation was performed to establish if this approach provides better optimised solutions than the deterministic approach. These comparative objective function values are given in the maintenance schedule tables 5, 6 and 7 showing that Fuzzy 'A' is marginally better than Non-fuzzy which in turn is marginally better than Fuzzy 'B' where the evaluation index values are more stringently set. However, it is important to note that the Fuzzy methods' parameter settings all reflect an increase in load through consecutive years.

Tables 5, and 6 are maintenance scheduling solutions for Fuzzy 'A' and Non-fuzzy, respectively, with $RR_{min}$ set at 10%. The difference in scheduling solutions...
between Fuzzy 'A' and Non-fuzzy was the inspection period for unit # 14. For this generating unit, there were 3 possible maintenance inspection start time intervals (otherwise termed as branching options) from the last time interval of September to the second time interval of October. Due to previous maintenance, a complete maintenance inspection requiring 6 time intervals was necessary. This scheduling difference came about because Fuzzy 'A' used relaxed evaluation index values, therefore satisfying the future year constraint. Also note that both methods deemed the last time interval in February to be infeasible for unit # 13 as denoted by the symbol 'X'. This occurs if any of the three pre-branching constraints (station location, unit location or min. res. cap.) are not satisfied. In this case, due to the output capacity of unit # 13 and the load level in this time interval, the loss of this unit for maintenance would result in an insufficient reserve capacity level.

Table 7 gives the maintenance scheduling solution for Fuzzy 'B' (IM = 0.98, 0.96 and 0.94) for RRmin = 10%. Although the comparative deterministic value is only marginally less optimal than that of the other 2 schedules shown, the maintenance times for various units differ considerably. This is because more stringent evaluation index requirements were chosen meaning that the programme took a different path to its optimal solution. When comparing this to the results of Fuzzy 'A' and Non-fuzzy, this illustrates that parameter adjustment affects solution configuration and feasibility, hence providing flexibility.

5. Conclusions

In the present paper, the authors have discussed and demonstrated the effectiveness of a new method for determining thermal power station maintenance scheduling which takes into account multi-year constraints and is based on Fuzzy theory. Its effectiveness was illustrated by comparing its results with an existing deterministic method.

(1) Due to the application of membership functions to represent load demand and reserve capacity, the proposed method provides operation and solution flexibility. Flexibility is provided in that the operator is able to express intentions with respect to load and reserve capacity levels and the easing of index evaluation settings increases solution feasibility. In addition, equalisation of an averaged reserve capacity containing the degree of uncertainty of load is achieved.

(2) The proposed method's longer computation time is partly due to the fact that in order to obtain this averaged value (as above), lengthy integration calculations are required.

(3) It is also important to note that the final solution obtained is done so by working through the generating units in listed order, therefore, the solution can only be termed as optimal with respect to this predetermined ordering.

(4) In order to further test the effectiveness of this method it is necessary to carry out further simulations on different system models to compare credibility of solutions. In addition to this, further work is required on membership function parameter selection policy. This is of course to a great extent dependent on individual system characteristics and configurations.

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