Flexible Maintenance Scheduling of Generation System by Multi-
Probabilistic Reliability Criterion in Korea Power System

Jeongje Park*, Jaeseok Choi†, Ungki Baek**, Junmin Cha*** and Kwang Y. Lee****

Abstract – A new technique using a search method which is based on fuzzy multi-criteria function is proposed for GMS (generator maintenance scheduling) in order to consider multi-objective function. Not only minimization of probabilistic production cost but also maximization of system reliability level are considered for fuzzy multi-criteria function. To obtain an optimal solution for generator maintenance scheduling under fuzzy environment, fuzzy multi-criteria relaxation method (fuzzy search method) is used. The practicality and effectiveness of the proposed approach are demonstrated by simulation studies for a real size power system model in Korea in 2010.

Keywords: Generator maintenance scheduling, Fuzzy set theory, Fuzzy multi-criteria functions

1. Introduction

The primary function of an electric power system is to provide electrical energy to its customers as economically as possible and with an acceptable degree of continuity and reliability.

It is, however, impossible to predict load exactly. A proper supply reliability all the time is not easy. Practically, the development of industrial utility has made the size of generation system huge and the system structure has been very complex. Therefore, problems about operation and planning of generation system are complicated[1]-[2].

Generator maintenance scheduling problem is an important planning problem that affects both economy and reliability for operation and planning of generating systems. Optimal maintenance scheduling is able, not only to raise supply and reserve rate, but also to postpone the period of construction cost of the generators, production cost and maintenance scheduling cost. The important point of generator maintenance scheduling is how to choose the objective function, and until now, maintenance scheduling problem has been built using the following objective functions [3]-[4] ;

(1) Generation Cost Minimization Method
(2) Levelized Risk Method
(3) Levelized Reserve Method
(4) Multi-criteria Functions Method

Additionally, recently methods for considering the capacity of transmission line have been proposed in [5]-[6].

In the present study, the method of maintenance scheduling by fuzzy search method has been developed. It is expected that more flexible solution can be obtained because fuzzy set theory that can reflect the subjective decision of decision-maker has been used in this study[7]-[11]. An alternative method for flexible GMS using various kinds of objective functions is proposed in this paper. The effectiveness of the proposed approach are demonstrated by simulation studies of a real size power system model.

2. Fuzzy Search Method

The fuzzy decision set D resulting from fuzzy sets of q fuzzy goals, G1, G2, ..., Gq and fuzzy sets of p fuzzy constraints, C1, C2, ..., Cp is as intersection defined as follows.

\[ D = \bigcap_{i=1}^{p} G_i \cap \bigcap_{j=1}^{q} C_j \]  

(1)

The membership function \( \mu_D \) resulting from the membership function of fuzzy sets of goals and constraints is defined as follows [12]:

\[ \mu_D(x) = \min_{i\in P} \min_{j\in Q} \mu_{G_i} \cdot \min_{j\in Q} \mu_{C_j} \]  

(2)

where, \( \min \) is an abbreviation of minimum.

If the fuzzy mathematical programming problem consists of finding maximum point of the membership function of the fuzzy decision set D, the optimal solution can be obtained as:

\[ \mu_D(X^*) = \max \mu_D(X) \]  

(3)

Where, \( X^* \) is the optimal decision solution, and \( \max \) is an abbreviation of maximum.

The vector form in Eq.(3) can be rewritten as:
In order to solve this problem by using the fuzzy search method, the principle of optimality can be applied after Eq.(4) can be reformulated as:

\[
\mu_{P}(X_{1}, X_{2}, ..., X_{n}) = \max_{X_{1}, X_{2}, ..., X_{n}} \mu_{P}(X_{1}, X_{2}, ..., X_{n})
\]  

(4)

where, \(X_i\) : decision variable, \(F = G + C\) (algebraic sum of fuzzy sets)

\[
\mu_{P}(X_{1}, X_{2}, ..., X_{n}) = \max_{X_{1}, X_{2}, ..., X_{n}} \left[ \min\{\mu_{P}(X_{1}, X_{2}, ..., X_{n})\} \right]
\]

(5)

where, \(X_i\) : decision variable, \(F = G + C\) (algebraic sum of fuzzy sets)

Given aspiration level of decision-maker for the probabilistic production cost Eq.(8) can be represented as fuzzy goal function form as:

\[
F\{ E_{n}F(U_{n}) \} \leq Z
\]

(10)

where, \(Z_{01}\) : aspiration level of decision-maker for the production cost

(2) Minimization of LOLE

Minimizing of LOLE is defined;

\[
\text{Minimize } Z_{2} = \text{LOLE} = \Phi_{n0}(U_{n0}) \quad [\text{pu}]
\]

(11)

And also, Eq.(11) can be represented as fuzzy goal function form as:

\[
Z_{2} \geq Z_{02}
\]

(12)

where, \(Z_{02}\) : aspiration level of decision-maker for LOLE

(3) Maximization of Minimum SRR

Maximizing of minimum SRR(Supply Reserve Rate) in 52 weeks should be considered. It can be defined as:

\[
\text{Maximize } Z_{3} = \text{minimum}(SRR_{n}) \quad [%]\n\]

(13)

where, \(SRR_{n} = \frac{(IC-MCAP_{n}-PD_{n})x100}{PD_{n}}\)

(4) Maximization of EIR

Maximizing of EIR(Energy Index of Reliability) can be considered as:

\[
\text{Maximize } Z_{4} = \text{EIR} \quad [\text{pu}]
\]

(14)

where, \(EIR = 1 - \frac{EENS}{ESD}\)

EENS: expected energy not served [MWh]
ESD: expected energy for demand [MWh]

And also, Eq.(12) can be represented as fuzzy goal function form as:

\[
Z_{4} \geq Z_{04}
\]

(15)

where, \(Z_{04}\) : aspiration level of decision-maker for EDNS.
3.2 Constraints

(1) Boundary Conditions

\[
X(1) = 0 \\
X(T + 1) = \text{col}([MD_1, MD_2, MD_3, ..., MD_m])^T
\]

Where, \( \mathbf{0} \): zero vector
\( MD_i \): time period asked for maintenance of \( i \) unit

(2) Constraints for Maintenance Possible Time Period

\[
U_i(t) = \begin{cases} 0 & \text{if } t < MS_i \text{ or } t > MF_i + MD_i \\ 1 & \text{if } MS_i \leq t \leq MF_i + MD_i \end{cases}
\]

where, \( MS_i \): starting time for maintenance of first possible maintenance time period of \( i \) unit
\( MF_i \): starting time for maintenance of last possible maintenance time period of \( i \) unit

(3) Constraints for Maintenance Possible Time Period

\[
\sum_{i=1}^{n} U_i(t) \leq 1
\]

where, \( P_k \): set of generators at \( k \) power plant

(4) Constraint of Maintenance Equipments

\[
\sum_{i=1}^{n_k} U_i(t) \cdot M_{ii} \leq M_A(t)
\]

where, \( k \): the number of the kinds of maintenance equipment \( k = 1, 2, ..., K \)
\( l \): number of maintenance scheduled time of \( i \) unit
\( M_A(t) \): amount of \( k \) maintenance equipment available within \( t \) stage
\( M_i \): amount of \( k \) maintenance equipment within \( i \) maintenance time period of \( i \) unit

4. Establishment of Membership Function

(1) Membership Function of Fuzzy Set for The Production Cost is Defined as:

\[
\mu_{C}(X(t-1), u(t)) = \begin{cases} 1 & \Delta C(\cdot) \leq 0 \\ e^{-W_C \Delta C(\cdot)} & \Delta C(\cdot) > 0 \end{cases}
\]

where, \( \Delta C(\cdot) \): membership function of fuzzy set for production cost
\( \Delta C(\cdot) = F(X(t)) - \text{Casp}(t) \) / \( \text{Casp}(t) \)
\( \text{Casp}(t) \): aspiration level for production cost at \#t stage
\( W_C \): weighting factor of the membership function for production cost

(2) Membership Function of Fuzzy Set for the Reliability LOLE is Defined as:

\[
\mu_{LOLE}(X(t-1), u(t)) = \begin{cases} 1 & \Delta R(\cdot) \leq 0 \\ e^{-W_{LOLE} \Delta R(\cdot)} & \Delta R(\cdot) > 0 \end{cases}
\]

where, \( \mu_{LOLE}(\cdot) \): membership function of fuzzy sets for reliability LOLE
\( \Delta R(\cdot) = \{ \text{RES}(X(t)) - \text{REQ}(t) \} / \text{REQ}(t) \)
\( \text{REQ}(t) \): aspiration level for reliability at \#t stage
\( W_{LOLE} \): weighting factor of the membership function for reliability LOLE

(3) Membership Functions of Fuzzy Set for the Reliability SRR is Defined as:

\[
\mu_{SRR}(X(t-1), u(t)) = \begin{cases} 1 & \Delta R(\cdot) \leq 0 \\ e^{-W_{SRR} \Delta R(\cdot)} & \Delta R(\cdot) > 0 \end{cases}
\]

where, \( \mu_{SRR}(\cdot) \): membership function of fuzzy sets for reliability SRR
\( \Delta R(\cdot) = \{ \text{RES}(X(t)) - \text{REQ}(t) \} / \text{REQ}(t) \)
\( \text{REQ}(t) \): aspiration level for reliability SRR at \#t stage
\( W_{SRR} \): weighting factor of the membership function for reliability SRR

(4) Membership Function of Fuzzy Set for the Reliability EIR is Defined as:

\[
\mu_{EIR}(X(t-1), u(t)) = \begin{cases} 1 & \Delta R(\cdot) \leq 0 \\ e^{-W_{EIR} \Delta R(\cdot)} & \Delta R(\cdot) > 0 \end{cases}
\]

where, \( \mu_{EIR}(\cdot) \): membership function of fuzzy sets for air pollution fuzzy set
\( \Delta R(\cdot) = \{ \text{RES}(X(t)) - \text{REQ}(t) \} / \text{REQ}(t) \)
\( \text{REQ}(t) \): aspiration level for reliability EIR at \#t stage
\( W_{EIR} \): weighting factor of the membership function for reliability EIR

5. Solution Procedure by the Fuzzy Search Method

Fuzzy decision set \( D \) applied to the Eq.(1) can be formulated as:

\[
D = C \cap R1 \cap R2 \cap R3
\]
\[
\mu_d(X(t)) = \max\{\min\{\mu_1(\cdot), \mu_{01}(\cdot), \mu_{02}(\cdot), \mu_{03}(\cdot), \mu_{04}(\cdot), \mu_{05}(X(t-1))\}\} (25)
\]

where, \(X(t) = X(t-1) + u(t)\)
\(\mu_d(X(0)) = 1.0\)
\(\mu_{0}(\cdot):\) membership function of fuzzy set for decision function

6. Case Study

6.1 Input Data

The proposed method was applied to the Korea power system on 2010 and probability production cost was calculated by the cumulant method. Fig. 1 represents year load curve pattern which has weekly load peaks on 2010 in the KEPCO system. The year peak load in this year is forecasted as 62,852MW. Table 1 shows generation system in 2010.

Aspiration levels and weighting factors for probability production cost, deterministic and probabilistic reliability indices shown in Table 1 has been used for this case study.

Fig. 1. Year load curve pattern with weekly load peaks.

Table 1. Input data (aspiration level & weighting factor)

<table>
<thead>
<tr>
<th>aspiration</th>
<th>weighting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z_{01})</td>
<td>(25,400,000)(10^6)Won</td>
</tr>
<tr>
<td>(Z_{02})</td>
<td>10.0[%/year]</td>
</tr>
<tr>
<td>(Z_{03})</td>
<td>5.5[days/year]</td>
</tr>
<tr>
<td>(Z_{04})</td>
<td>0.99990[pu]</td>
</tr>
</tbody>
</table>

6.2 Output Data

The results are in appendix. Fig. 2 shows convergence of the membership value of objective function according to iterations. The objective function which indicates the satisfaction degree of decision-maker converges over 0.9 from fourth iteration. The convergence maximum \(\mu_{\max}\) is 0.952 at fourteen iterations. Fig. 6 is a representation of maintenance of power and supply reserve rates for each week.

![Fig. 2. Convergence of the objective function (\(\mu_{\max}\)).](image)

![Fig. 3. Cost and EIR.](image)

![Fig. 4. SRR and standard deviation.](image)

![Fig. 5. LOLE and standard deviation.](image)
6.3 Parametric Analysis

**Case study I**

Table 3 shows a parametric analysis result according to changing of aspiration level of SRR. As the aspiration level of the SRR is higher (stricter), the propose method asks for sacrifices of other objective values, cost, LOLE and EIR in order to avoid sharp decreasing of the satisfaction level as possible as. As it is, the cost and LOLE are asked for their increasing a little bit. EIR is asked for its decreasing a little bit. Therefore, the sharp decreasing of satisfaction level due to higher aspiration level of the SRR may be avoided overall. Eventually, more flexible solution is obtained using proposed method.

<table>
<thead>
<tr>
<th>Case</th>
<th>Cost [10^6 Won]</th>
<th>SRR [%]</th>
<th>LOLE [days/year]</th>
<th>EIR [pu]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>15,400,000</td>
<td>10.0</td>
<td>5.5</td>
<td>0.99900</td>
</tr>
<tr>
<td>Case 2</td>
<td>15,400,000</td>
<td>12.0</td>
<td>5.5</td>
<td>0.99900</td>
</tr>
<tr>
<td>Case 3</td>
<td>15,400,000</td>
<td>14.0</td>
<td>5.5</td>
<td>0.99900</td>
</tr>
</tbody>
</table>

**Table 4. Aspiration Levels and Weighting Factors of Membership Functions for Cases 5 and 6**

<table>
<thead>
<tr>
<th>Case</th>
<th>Cost [10^6 Won]</th>
<th>SRR [%]</th>
<th>LOLE [days/year]</th>
<th>EIR [pu]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 5</td>
<td>15,200,000</td>
<td>10.0</td>
<td>5.5</td>
<td>0.99900</td>
</tr>
<tr>
<td>Case 6</td>
<td>15,000,000</td>
<td>10.0</td>
<td>5.5</td>
<td>0.99900</td>
</tr>
</tbody>
</table>

**Table 5. Results According to Changing of Aspiration Level of Production Cost**

<table>
<thead>
<tr>
<th>Case</th>
<th>Cost [10^6 Won]</th>
<th>SRR [%]</th>
<th>LOLE [days/year]</th>
<th>EIR [pu]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>15,476,098</td>
<td>9.957</td>
<td>5.554</td>
<td>0.99328</td>
</tr>
<tr>
<td>Case 5</td>
<td>15,472,839</td>
<td>9.665</td>
<td>5.697</td>
<td>0.99298</td>
</tr>
<tr>
<td>Case 6</td>
<td>15,468,876</td>
<td>9.397</td>
<td>5.844</td>
<td>0.99267</td>
</tr>
</tbody>
</table>

**Case study II**

Table 5 shows a parametric analysis result according to changing of aspiration level of production cost. As the aspiration level of the cost is lower (stricter), the propose method asks for sacrifices of other objective values, SRR, LOLE and EIR in order to avoid sharp decreasing of the satisfaction level as possible as. As it is, the LOLE is asked for their increasing a little bit. The SRR and EIR are asked for their decreasing a little bit. Therefore, the sharp decreasing of satisfaction level due to higher aspiration level of the cost may be avoided overall. Eventually, more flexible solution is obtained using proposed method.

### 7. Conclusion

A new technique using a search method which is based on fuzzy multi-criteria function is proposed for the GMS problem in order to consider multi-objective function. Not only minimization of probabilistic production cost but also various kinds of system reliability indices levels are considered simultaneously for fuzzy multi-criteria function. To obtain an optimal flexible solution for generator maintenance scheduling under fuzzy environment, fuzzy multi-criteria relaxation method (fuzzy search method) is used. When an aspiration level is stricter, the propose method suggests another optimal solution that avoids to decrease satisfaction level(objective function) sharply even if other objective values are asked for their sacrifices a little bit. It shows, eventually, that more flexible solution is obtained using proposed method. The practicability and effectiveness of the proposed method are demonstrated by simulation results on real size power system model in Korea in 2010.

### Acknowledgements

This work has been supported by KESRI(09309), which
is funded by Korea Western Power Co. The support of the Advanced Power Network Reliability Research Center (APRRC) is acknowledged.

### Appendix

#### Table 1. Generation system in Korea in 2010

<table>
<thead>
<tr>
<th>NO.</th>
<th>Name</th>
<th>ID</th>
<th>Cap. [MW]</th>
<th>POR</th>
<th>A (kn/kVA)</th>
<th>B (kn)</th>
<th>C (kn/kVA)</th>
<th>Fuel cost [10^3won/Gcal]</th>
<th>Duration of Maint. [weeks]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WABN</td>
<td>2</td>
<td>300</td>
<td>0.166</td>
<td>1.991</td>
<td>0.994</td>
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<td></td>
</tr>
<tr>
<td>2</td>
<td>WLSN</td>
<td>3</td>
<td>670</td>
<td>0.166</td>
<td>2.082</td>
<td>0.946</td>
<td></td>
<td></td>
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<tr>
<td>3</td>
<td>XSKN</td>
<td>4</td>
<td>500</td>
<td>0.166</td>
<td>2.019</td>
<td>1.019</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>ULIN</td>
<td>5</td>
<td>900</td>
<td>0.196</td>
<td>1.508</td>
<td>1.212</td>
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<td>5</td>
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<td>1000</td>
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<td>10</td>
<td>WABN</td>
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<td>225</td>
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<td>11</td>
<td>WABN</td>
<td>22</td>
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<td>1.249</td>
<td>0.887</td>
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</tbody>
</table>

#### Table 2. shows the results obtained the fuzzy set based method for GMS proposed in this paper. In the GMS Table, dotted lines and cross marks mean the weeks of available
maintenance scheduling and the weeks of maintenance scheduling respectively. It was assumed that generators whose operations start since 2010 need not be included in the maintenance scheduling.

Table 2. Result

<table>
<thead>
<tr>
<th>No.</th>
<th>MM</th>
<th>CAP</th>
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<th>MM</th>
<th>CAP</th>
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References


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