A Study on Coordinated Generation Maintenance Scheduling in Competitive Electricity Markets

Chang-Gi Min *, Yu Chang Kim *, Do-Han Kim *, Mun-Kyeom Kim † and Jong-Keun Park *

Abstract – A new approach to coordinated generation maintenance scheduling (GMS) in competitive electricity market, based on game theoretic framework, is presented. The main contribution of this paper can be focused on formulating the problem of ISO and modeling the coordination procedure. In competitive markets, the objective of generation company (genco) is to maximize the profits. The objective of ISO is to ensure reliability by increasing reserve capacity during peak period. The Genco and ISO determine their own GMS according to each objective, and then GMS of Genco is compared to that of ISO with ISO reliability criteria. If they are close enough, the GMS of Genco is determined as final GMS. Otherwise the coordination procedure is repeated until the GMS of Genco satisfies the ISO reliability criteria. Numerical results for two-Genco system are used to demonstrate the applicability of this framework for maintenance scheduling problem.

Keywords: Electricity market, Generation maintenance scheduling, Coordination, Non-cooperative game, Nash equilibrium

1. Introduction

Generation Maintenance Scheduling (GMS) is an important part of power system operation planning. In centralized electric power system, the GMS is determined only by the system operator and imposed to generation company (genco). After the power industry restructuring, an utility is divided into several generation companies (gencos) and network companies, thus, GMS becomes complicated problem related with many utilities [1]. In competitive electricity market environment which the management of genco and ISO is separated, each genco determines its GMS not considering any system security of reliability aspects. Such GMS would be designed for their own interests and may not be in the interest of system security. Jin-Ho et al. present a new game-theoretic framework to analyze maintenance strategy of each genco in competitive electricity markets without consideration of reliability aspects [2]. Meanwhile, security and reliability of the power system may be degraded if the GMS is determined by each genco for its own generators, especially in those systems with low reserve margin. If the GMS of genco is not well coordinated or regulated, the system security and reliability cannot be guaranteed because too much maintenance capacity can be arranged at the same period and this consequently leads to insufficient operating reserve.

In real markets, the maintenance windows for generators are scheduled by coordination between gencos and reliability-centered ISO, although the extent of coordination depends on the electricity market environment of each country. This means that the maintenance windows for generators are determined not only by genco but also by system operator. It is determined through multiple interactions among the market parties such as gencos and ISO [3], [4]. The coordination procedure how ISO adjusts the individual generators’ MS and how each genco responds to the adjusted schedule is important. The ISO coordinates all independent schedules from gencos, and formulates a system-wide maintenance plan that is feasible, reliable, and acceptable to all parties. A comprehensive of the problem is discussed well in [5].

This paper proposes the coordination procedure between ISO and gencos in competitive electricity markets. The gencos determine optimum GMS of generators in competitive environment. The ISO also determines its own reliability-centered GMS. The GMS specified by each genco is handed to ISO and compared with the ISO’s own maintenance scheduling. If they close enough, it will be approved; otherwise ISO will send the information of coordination result and each genco will be asked for rescheduling GMS. In this paper, the game theoretic framework on GMS problem is used to analyze behaviors of gencos [2]. A new approach to coordination procedure and ISO objective function is presented.

The rest of this paper is organized as follows. In Section
2. GMS Game Formulation

2.1 Basic Concept

GMS problem is to determine maintenance windows for all generators over planning horizon. In competitive markets, the GMS problem can be modeled as a non-cooperative game where individual gencos decide the maintenance strategy (i.e. maintenance window) for their generator(s) for a given horizon to maximize their expected profit from hourly energy auction market [2]. The player corresponds to each genco, and the strategy of each genco is generators states (i.e. maintenance or not). The payoff of each player is the profit from the energy auction market. The optimal maintenance strategy is attained by the Nash equilibrium of the game. In this game, bidding strategy of each genco in hourly energy auction market is not considered. Instead, all generators are assumed to submit offer price curve to the hourly energy auction market with their marginal cost curve ranging from minimum to maximum generation quantity. This offer price is open to the public since the marginal costs and minimum/maximum generation quantity are generally considered as open information. Any kind of transmission constraints are not taken into account. Besides, demand curve is assumed to be known and forced outage rates for generators are not considered, because no uncertainty is considered, nevertheless unit forced outage rates can be considered easily.

2.2 Payoff

The payoff represents the welfare of the players (gencos) at the end of the game. They are the basis on which each player chooses his maintenance strategy. The payoff of a player is defined as the sum of his generator’s profits from the auctions over the planning horizon. The profits are calculated by subtracting the sum of production cost and maintenance cost from revenues which is gathered hourly energy auction. Let \( p'(\cdot) \) and \( g'_{i,j}(\cdot) \) be the market clearing price and the generation quantity allocated to the generator-\( j \) of genco-\( i \) at hour \( t \), respectively. Also, let \( f_{i,j}(\cdot) \) and \( m_{i,j}(\cdot) \) denote the production cost and the maintenance cost of the generator-\( j \) of genco-\( i \), respectively. Since we do not explicitly consider bidding strategy of each genco, each outcome of hourly energy auction market is determined only by the maintenance strategy of generators. Therefore, the payoff of genco-\( i \), \( \Pi_i \), can be defined implicitly as a function of the strategy profiles \( \bar{x} \) as (1)

\[
\Pi_i(\bar{x}) = \sum_{k=1}^{T} \left( \sum_{t=1}^{\text{168}} \left[ p'(\bar{x}_t^k) \cdot q'_{i,j}(\bar{x}_t^k) - f_{i,j}(\bar{x}_t^k) \right] - \sum_{j=1}^{N_i} m_{i,j}(\bar{x}_t^k) \right)
\]

where \( k \) means stages(week), that is, \( k=1,2,\ldots,T \) and each stage consists of 168 hours. \( N_i \) implies the number of generators owned by genco-\( i \). The required maintenance window length of each generator is taken into account in the maintenance strategy \( \bar{x} \). The production cost \( f_{i,j}(\cdot) \) in (1) is a function of the generation quantity \( g'_{i,j}(\cdot) \), and although the cost \( f_{i,j}(\cdot) \) is stated as a function of strategy \( \bar{x} \), implicitly. The quantity \( g'_{i,j}(\cdot) \) can be obtained explicitly as a result of each hourly auction. The payoff of genco-\( i \) at stage \( k \), \( \Pi_{i,k} \) can also be expressed by the strategies \( \bar{x}_t^k \), as (2)

\[
\Pi_{i,k}(\bar{x}_t^k) = \sum_{t=1}^{\text{168}} \left[ p'(\bar{x}_t^k) \cdot q'_{i,j}(\bar{x}_t^k) - f_{i,j}(\bar{x}_t^k) \right] - \sum_{j=1}^{N_i} m_{i,j}(\bar{x}_t^k)
\]

Therefore, the total payoff of genco-\( i \) over the planning horizon, defined in (1), can be simplified as follows

\[
\Pi_i = \prod_{k=1}^{T} \Pi_{i,k}(\bar{x}_t^k)
\]

2.3 Solution

Nash equilibrium is widely considered as the solution of the non-cooperative dynamic games. The extended solution concept of subgame perfect equilibrium is applied to analyze the strategic behaviors of gencos in the GMS game that is characterized as a dynamic game. Let \( \Pi_{i,j}^k(\cdot) \) be player-\( i \)'s payoff of subgame-\( j \). Then the solution profile can be represented by (4).
\[
\prod_{i \in S_f} (Nash_i, S^*_{\text{Nash}}) \geq \prod_{i \in S_f} (Nash_i, S^*_{\text{Nash}}) \quad \text{for} \quad i = 1, 2, \ldots, N, \quad \forall f, \quad \forall S^*_f \in S_f \quad (4)
\]

where
\[
S^*_{\text{Nash}} = [Nash_1, Nash_2, \ldots, Nash_{i-1}, Nash_{i+1}, \ldots, Nash_N]
\]

\( N \) means total number of gencos, \( S_f \) is the total feasible maintenance strategy set.

### 3. Problem of ISO

During peak period, ISO would try to attain the reserve capacity as many as possible. Because objective of the ISO is to maximize reliability [4], that is, this problem is to maintain the adequate level of reserve throughout the planning horizon. It is reasonable that ISO will increase reserve capacity during the peak period and decrease during the off-peak period because there exists the reserve capacity constraint. Although the market situation is competitive, ISO would determine the GMS only to maximize the reliability over the planning horizon. Under the assumption, ISO is trying to obtain the high reserve margin during the peak period while ISO is trying to maintain relatively low reserve margin during the off-peak period. According to this meaning, GMS problem of ISO can be modeled as the following simple optimization problem (5).

\[
\text{Max } \text{Variance} \left( \sum_{k=1}^{168} \sum_{t=1}^{\tau_{k,t}} \sum_{i=1}^{N} \sum_{j=1}^{N} q_{i,j}^{\text{max}}(s) + d_{k,t}^{s} \right)
\]  

(5)

where \( d_{k,t}^{s} \) implies the demand at time \( t \), during the planning horizon, generation quantity \( q_{i,j}^{\text{max}}(s) \) means available capacity of generator-\( j \), genco-\( i \) at time \( t \) determined by strategy \( s \) which contains all generators’ states, maintenance or not. The required maintenance window length of each generator taken into account in the maintenance strategy \( s \) is a basic constraint of this optimization problem. As reliability constraint widely used by system operator, supply reserve ratio (SRR) constraint is represented in (6).

\[
R^{\text{eq}}(k,t) = \frac{\left( \sum_{i=1}^{N} \sum_{j=1}^{N} q_{i,j}^{\text{max}}(s) - d_{k,t}^{s} \right)}{d_{k,t}^{s}} \geq R^{\text{eq}}(k,t) \quad \forall k, \forall t
\]  

(6)

The ISO ensures the SRR above a specified threshold for all period \( k \) and subperiod \( t \). The left-hand side of (6) is net SRR calculated for each period \( k \) and subperiod \( t \). Also, the right-hand side of (6) is required SRR which means threshold value for the system. Naturally, depending on the system characteristics, this threshold value can be chosen differently. Only the GMS plan satisfying the required SRR can be included in the feasible GMS plan profile in (4). The objective function of ISO in (5) can be represented by (7). The computational process is omitted in this paper.

\[
\text{Max } s \left( \frac{1}{168T} \sum_{k=1}^{168} \sum_{t=1}^{\tau_{k,t}} \left( Q_{i,j}^{\text{max}}(s) \right)^2 + d_{k,t}^{s} \right) \\
- \frac{1}{(168T)^2} \left[ \left( \sum_{k=1}^{168} \sum_{t=1}^{\tau_{k,t}} Q_{i,j}^{\text{max}}(s) \right)^2 \right] \\
+ 2 \left( \sum_{k=1}^{168} \sum_{t=1}^{\tau_{k,t}} Q_{i,j}^{\text{max}}(s) \right) \left( \sum_{k=1}^{168} \sum_{t=1}^{\tau_{k,t}} d_{k,t}^{s} \right)
\]  

(7)

where

\[
Q_{i,j}^{\text{max}}(s) = \sum_{j=1}^{N} \sum_{i=1}^{N} q_{i,j}^{\text{max}}(s)
\]

### 4. Solution Procedure

The following procedure allows gencos to satisfy their maximum-profit objective, while ISO’s objective of ensuring reliability is achieved in each week of the year. Solution procedure is followed by these steps. This procedure to obtain final GMS is considerably similar to the procedure discussed in [4].

**Step 1**: The ISO solves the maintenance scheduling problem explained in Section 3, with objective function in (7) throughout the weeks of the year. The results obtained from this step is called ISO-GMS plan.

**Step 2**: Each genco determines independently its maintenance scheduling according to the procedure explained in Section 2, with the target of maximizing its own profit. The result obtained from this step is called Genco-GMS plan.

**Step 3**: The ISO compares the ISO-GMS plan with the Genco-GMS plan. If they are close enough to satisfy the coordination criteria (Section 4.1), the procedure ends up. Otherwise, ISO calls for rescheduling of Genco-GMS plan so that the Genco-GMS plan approaches the ISO-GMS plan.
4.1 Coordination criteria

If Genco-GMS and ISO-GMS are not close enough, the Genco is asked for rescheduling his GMS plan to meet the coordination criteria. Coordination criterion factor is represented as \( \varepsilon \), which will be compared with RMSE (root mean square error) between the supply reserve ratio (SRR) of Genco-GMS plan and that of Genco-GMS plan for whole period \( k \), subperiod \( t \). This root mean square error can be expressed by (8)

\[
\delta = \text{RMSE}(R_{\text{ISO-GMS}}, R_{\text{Genco-GMS}}) \]

where,

\[
\text{RMSE}(R_{\text{ISO-GMS}}, R_{\text{Genco-GMS}}) = \sqrt{\frac{1}{168T} \sum_{t=1}^{168} \sum_{k=1}^{T} (R_{\text{ISO-GMS}}(k, t) - R_{\text{Genco-GMS}}(k, t))^2} \tag{8}
\]

Then RMSE, \( \delta \) is compared with coordination criteria factor, \( \varepsilon \). If \( \delta < \varepsilon \), there is no need to coordinate the Genco-GMS plan. Otherwise, Genco-GMS plan must be coordinated. It should be noted that determining the coordination criteria factor, \( \varepsilon \) can be an important problem because final approval is depending on \( \varepsilon \) value. In this paper, its proper values are located within 60 ~ 70. This result is experimentally attained by using 2008 year data in South Korea [6]. It can be varied with system situation and more research about this value will remain as future work.

When Genco-GMS plan does not meet the coordination criteria, this information, containing all Gencos’ GMS plans excluded by ISO, is known to all Gencos and at the same time rescheduling GMS is requested. Because ISO have authority to make a final approval of Genco-GMS, this procedure must be carried out until Genco-GMS satisfy the coordination criteria. Coordination procedure is achieved by this iteration scheme. Fig. 1 summarizes the solution procedure of the GMS problem including the coordination procedure.

5. Case study

Two-Genco system is used simply to demonstrate the applicability of the coordinated GMS problem in competitive electricity markets. The information about generators of each Genco is shown in Table 1. This data is based on [7].

The cost function of each generator is assumed to be a quadratic function such that \( f_{i,j}(\cdot) \) is represented as (9)

\[
f_{i,j}(q_{i,j}) = c_{i,j} + b_{i,j} q_{i,j} + a_{i,j} (q_{i,j})^2 \tag{9}
\]

where \( a_{i,j}, b_{i,j}, \) and \( c_{i,j} \) are cost coefficients. Actually, cost coefficients need to be compensated according to the easy-variable fuel cost which takes large portion of the generation cost. In this study, however, it is assumed that cost coefficients are fixed over the horizon to simplify the problem. In Table 1, \( w_{i,j} \) denotes the required maintenance window length for the generator-\( j \) of genco-\( i \), which is expressed in weeks. For simplicity, the maintenance cost of individual generator, that is, \( m_{i,j}(\cdot) \) in (1) is not considered in this example. The planning horizon is 52 weeks and therefore there exists 8736 (168x52) hourly energy auctions in this example. 10% is selected as a required SRR in (6), and this value is based on Korea power system [8]. \( \varepsilon \) value is selected as 70 based on [6]. The demand profile is shown in Fig. 2. Its pattern is based on [7]. In Fig 2, the peak demand period is shown during 2~6 weeks and 32~36 weeks.

<table>
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<th>Table 1. Data of generators</th>
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<tr>
<td>Genco</td>
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<tr>
<td>Genco-1</td>
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<td>Genco-1</td>
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<td>Genco-2</td>
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Fig. 1. Solution procedure of GMS problem.
ISO-GMS plan and Genco-GMS plan are determined according to the solution procedure (Section 4). Fig. 3 shows comparison between both cases for the SRR values during the one year.

During 8 to 10 weeks, the SRR of the Genco-GMS is shown below 10%, while ISO-GMS is above 40%. This can be a threat to the system reliability because this period of time is close to winter peak period shown in Fig. 2. It means that Genco-GMS is focused on profit maximization too much without considering system reliability at that period. So it needs to be coordinated by ISO. As seen from Fig 3, the SRR of Genco-GMS is very different with that of ISO-GMS. So rescheduling is requested repeatedly until Genco-GMS satisfies the coordination criteria condition. That is, when RMSE in (8) of both cases is larger than coordination criteria factor, Genco-GMS is approved as final GMS of that year. Table 2 shows the final GMS result, which is coordinated repeatedly by ISO.

### Table 2. Result of final approved GMS plan

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<tbody>
<tr>
<td>g1.1</td>
<td>220</td>
<td>12-16</td>
<td>g2.1</td>
<td>253</td>
<td>17-21</td>
</tr>
<tr>
<td>g1.2</td>
<td>192</td>
<td>41-44</td>
<td>g2.2</td>
<td>181</td>
<td>37-40</td>
</tr>
</tbody>
</table>

| Payoff[$] | 49,009 | 73,509 |

In Table 2, maintenance schedules of each generator and the corresponding payoffs are determined. It is confirmed that the coordinated maintenance window of each generator is located in off-peak period.

### 6. Conclusion

A new approach to coordinated generation maintenance scheduling in competitive electricity market based on game theoretic framework is presented. The main contribution of this paper is to formulate the problem of ISO and model coordination procedure. The ISO’s objective is to ensure the system reliability by increasing reserve capacity during peak period and decreasing reserve capacity during off-peak period while Gencos’ objective is to maximize the profits over the planning year. Genco and ISO determine their own GMS according to each objective. Then GMS of Genco is compared to that of ISO with ISO reliability criteria. If they are close enough, the GMS of Genco is determined as final GMS. Otherwise coordination procedure is repeated until GMS of Genco satisfies the reliability criteria. From the numerical results of case study, it is shown that this model can be helpful to ensure the system reliability during peak period. So applicability of the basic idea is confirmed. The problem about reliability criteria determination is also remained as a future work.

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