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Game-theory-based generation maintenance scheduling in electricity markets

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ABSTRACT

This paper presents a novel approach to the (generation maintenance scheduling) GMS problem in electricity markets. The main contribution of this study is the modeling of a coordination procedure for an (independent system operator) ISO, based on a game-theoretic framework for the GMS problem. The GMS process of generation companies (Gencos) is designed as a non-cooperative dynamic game, and the Gencos' optimal strategy profile is determined by the Nash equilibrium of the game. The coordination procedure performed by the ISO is characterized by the use of a reliability assessment and a so-called 'rescheduling signal'. A numerical example for a three-Genco system is used to demonstrate the applicability of the proposed scheme to the GMS problem. The results obtained indicate that the GMS of a profit-oriented Genco can be modified to satisfy the reliability requirements of the ISO.

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1. Introduction

In vertically integrated power systems, utilities have determined a generation maintenance schedule (GMS) to minimize operating cost while ensuring system reliability. However, restructuring of the electric power industry has resulted in market-based approaches for unbundling services provided by self-interested entities, such as generation companies (Gencos), transmission companies (Transcos), and distribution companies (Discos). In a competitive environment, there are additional challenges for market participants to adopt strategic behaviors. An individual Genco establishes a GMS to maximize profits, and then a system-wide GMS is constructed from the distributed decision [1]. At the same time, each Genco develops its GMS without considering overall system reliability or security. Thus, an (independent system operator) ISO is confronted with the significant task of coordinating the GMS. In reality, the ISO carries out this task by applying compulsory measures to modify a Genco's GMS when necessary [2–4]. For instance, 'NERC Policy 4' provides a fundamental principle for the coordination procedure used by system

operators in the USA [5]. However, its scope may be changed according to the circumstances of a regional system.

There have been several studies on the GMS problem, including the coordination procedure [6–11]. The author of [6] addressed the coordination procedure between the ISO and other relevant entities by defining the GMS problem in comprehensive form. In Ref. [7], an iterative coordination method was suggested, based on economic rescheduling signals. Similar approaches to the coordination procedure were presented in Refs. [8–11]. These studies can be classified into two categories, depending on the type of rescheduling signal. One type is based on incentive/penalty, and the other on physical rescheduling signals (capacity constraint). In most studies, the former mechanism has been used to implement market-based procedures. A (maintenance bidding cost) MBC approach has also been suggested to model the coordination mechanism [11]. Nevertheless, none of these studies reflected any interactions among the Gencos in a competitive environment. Reciprocal interactions should be considered as a prominent part of the decision-making process of a profit-oriented Genco, since its profits are primarily affected by the competitive relationship.

Recently, there have been various studies of interactions such as bidding strategies and GMS strategies in electricity markets [12–21]. Game-theoretic approaches have been used to model the strategic behavior of Gencos. The authors of [20,21] have designed a GMS process based on game theory for a competitive market environment. In Ref. [21], an effect of the uncertainty associated

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Nomenclature	
Variables	
$d^{k,t}$	demand at hour- t in week- k [MW]
$f_{ij}^{k,t}(\cdot)$	production cost of generating unit- j of Genco- i at hour- t in week- k [\$]
$m_{ij}(\cdot)$	maintenance cost of generating unit- j of Genco- i [\$/MW]
$mc_{ij}^{k,t}(\cdot)$	marginal cost of generating unit- j of Genco- i at hour- t in week- k [\$/MWh]
$P_i(\cdot)$	payoff of Genco- i in planning horizon [\$]
$P^k(\cdot)$	payoffs of all Gencos in week- k [\$]
$P_{i,v}(\cdot)$	payoff of Genco- i for v -th iteration [\$]
$q_{ij}^{k,t}(\cdot)$	generation quantity allocated to generating unit- j of Genco- i at hour- t [MWh]
$R_{cal}^{k,t}$	calculated reserve ratio at hour- t in week- k
$R_{Gen,v-1}^{k,t}$	calculated reserve ratio by Genco's GMS at hour- t in week- k for $v-1$ iteration
$R_{ISO}^{k,t}$	calculated reserve ratio by ISO's GMS criterion at hour- t in week- k for $v-1$ iteration
S	a maintenance strategy profile in planning horizon, which is represented by a matrix $S = [(S_1)^{tr} (S_2)^{tr} \dots (S_T)^{tr}]$
S_i	a maintenance strategy of Genco- i in planning horizon, which is represented by a matrix $S_i = [(S_i^1)^{tr} (S_i^2)^{tr} \dots (S_i^T)^{tr}]$
S_{ISO}	a maintenance strategy profile of ISO for all generating units in planning horizon
S^f	set of all feasible maintenance strategy profiles of all Gencos in planning horizon
S^k	maintenance strategies of all Gencos in week- k , which is represented by a vector $S^k = [S_1^k S_2^k \dots S_N^k]$
S_i^k	a maintenance strategy of Genco- i in week- k , which is represented by a vector $S_i^k = [X_{i,1}^k X_{i,2}^k \dots X_{i,N_i}^k]$
$(S_i^k)^1$	first case among possible cases of a maintenance strategy of Genco- i in week- k
$(S_i^k)^l$	last case among possible cases of a maintenance strategy of Genco- i in week- k
S_i^{Nash}	a maintenance strategy of Genco- i in planning horizon by Nash equilibrium
S_{-i}^{Nash}	maintenance strategies of all Gencos except for Genco- i in planning horizon by Nash equilibrium, which is represented by a matrix $S_{-i}^{Nash} = [(S_1^{Nash})^{tr} (S_2^{Nash})^{tr} \dots (S_{i-1}^{Nash})^{tr} \dots (S_{i+1}^{Nash})^{tr} \dots (S_N^{Nash})^{tr}]$
$X_{ij}^k(\cdot)$	a maintenance strategy of generating unit- j of Genco- i in week- k (unit on maintenance = 1, otherwise = 0)
$\gamma_v^{k,t}$	weighting factor for calculating incentive (or penalty) at time- t in week- k for v -th iteration
$\delta_v^{k,t}$	difference of reserve ratio between GMS criterion and Genco's GMS at time- t in week- k for v -th iteration
$\rho^{k,t}(\cdot)$	market clearing price at time- t in week- k [\$/MWh]
Constants	
a_{ij}	quadratic coefficient of generation cost [MWh ² /]\$]
b_{ij}	linear coefficient of generation cost [MWh/\$]
c_{ij}	constant coefficient of generation cost [\$]
H	number of hours in 1 week (168 h)
n	maximum iteration number of coordination procedure
N	number of Gencos
N_i	number of generating units of Genco- i
q_{ij}^{max}	maximum capacity of generating unit- j of Genco- i [MW]
q_{ij}^{min}	minimum power output of generating unit- j of Genco- i [MW]
R_{req}	reserve ratio criterion (or required reserve ratio)
T	planning horizon [week]
W_{ij}	duration of maintenance for generating unit- j of Genco- i [week]
β_v	coefficient for calculating incentive (or penalty) for v iteration [\$/MW]
Indices	
i	Gencos
j	generating units of a Genco
k	week
t	time (in this work, a time represents a hour)
v	iteration number of coordination procedure (natural number)
Operator	
tr	transpose of a matrix

with cost was presented within a game-theoretic framework. However, previous studies have not taken into account the coordination procedure of the GMS process. When a GMS causes system reliability to deteriorate, it should be adjusted by the ISO. Therefore, a coordination procedure is necessary to formulate the GMS problem in a market environment.

This paper proposes a competitive GMS process with a coordination procedure for electricity markets. The proposed approach reflects the perspectives of both Gencos and the ISO in designing a solution to the GMS problem. The profit-seeking Gencos try to obtain the optimal maintenance schedule through the decision-making process, which is represented as a non-cooperative dynamic game. The reliability-centered ISO attempts to achieve a sufficient level of reserve capacity via the coordination procedure, which is implemented using a reliability assessment and a rescheduling signal. If a Genco's GMS satisfies the reliability

assessment, it receives final approval. Otherwise, the coordination procedure is repeated.

The remainder of this paper is organized as follows. Section 2 describes the GMS game of the Gencos in competitive electricity markets, and discusses the coordination procedure based on a rescheduling signal. Section 3 summarizes the solution procedure for obtaining the final GMS. Section 4 presents a numerical example, and conclusions are stated in Section 5.

2. Problem formulation

2.1. The GMS problem for Gencos

2.1.1. Basic concept

A Genco's GMS process has two primary characteristics in a competitive market, in which it acts as a price-taker.

First, a Genco's GMS affects its own profits by providing the hourly available capacity of the generating units over the planning horizon. If a unit is undergoing maintenance, its capacity cannot be offered to the market. Thus, the Genco considers the hourly market price set by the hourly demand–supply balance when planning the maintenance periods of its units. If the market price is high, the Genco is likely to decrease the number of units undergoing maintenance in order to reap as much profit as possible. Conversely, if the market price is low, a Genco is more willing to increase the number of units undergoing maintenance. In this way, the Genco's profits are implicitly drawn from maintenance period decisions based on the time-varying market price.

Second, a Genco's profit is associated with the GMS of other Gencos. Since the electricity market operates via a market-clearing mechanism, the market price and trading quantity are settled by total offers of available units at any given time. In this environment, units with the lowest offered price have the best chance of being accepted, and higher-priced units are more likely to be rejected. For that reason, the profitability of a given generating unit depends on the availability of the remaining units. For example, if many cheaper units are available at a certain time, conditions will be adverse for units whose generation cost is relatively high. In other words, a Genco's profits are considerably affected by the maintenance periods of other Gencos' units. Therefore, it is more reasonable for a Genco to determine its GMS in light of the strategies of other Gencos.

In this way, one Genco's profits depend on the GMS of other Gencos, as well as its own. Because of these features of the GMS decision-making process, we construct a model for a competitive GMS process based on non-cooperative game theory. This model can provide a suitable tool for analyzing the strategic behavior of Gencos in the electricity markets.

2.1.2. Structure

The GMS problem is to determine the maintenance period for all generating units over the planning horizon. The player strategy is a decision about the states of the generating units, and the payoff is defined as the profits obtained from (hourly energy auctions) HEAs. The scheduling horizon is decomposed into weeks, so that the week is the minimum unit of maintenance duration. The structure of this game model is shown in Fig. 1. The strategy profile consists of the GMS strategies of all of the Gencos each week, which determines the availability of generating units. All Gencos offer their available units to the HEAs each week. The Genco's payoff is determined by summing the payoffs each week, during which 168 HEAs (1 week equals 168 h) are opened.

Although all maintenance decisions are made statically at the same time, the maintenance period of each player is determined

sequentially over the weeks. Thus, the GMS problem can be described as a dynamic game in which each Genco determines its weekly GMS strategy within the planning horizon to maximize the payoffs. This model cannot be directly transferred to the GMS game problem. To formulate this problem unambiguously, it is necessary to make some assumptions, such as:

- The offering strategy of each Genco in the HEA markets is not considered.
- The offered prices of all generating units correspond to the marginal costs which are regarded as open information in the HEA markets.
- The capacities of all available generating units are offered to the HEA markets.

Fig. 2 provides an extensive representation of a subgame for week k . The dashed-line boxes denote the same information sets in the game. Each set contains the nodes represented as small solid-line boxes. The decision nodes of Genco-1 and Genco- N correspond to the root and terminal nodes of the game, respectively. Each Genco has multiple strategy options in week k , ranging from the first strategy $(S_i^k)^1$ to the last strategy $(S_i^k)^l$, at every node in its information set. The Gencos simultaneously select one strategy from among their options. Then, a path is drawn from the root to the terminal node by combining the strategies of all of the Gencos. The path based on the decisions of all of the Gencos provides information about the state of all of the generating units (i.e., the availability of all generating units). The available units are offered to

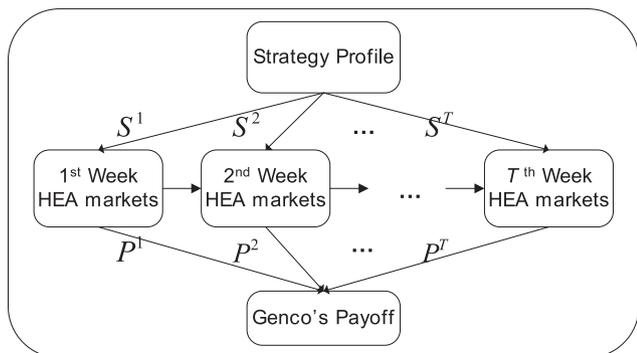


Fig. 1. Structure of the GMS game.

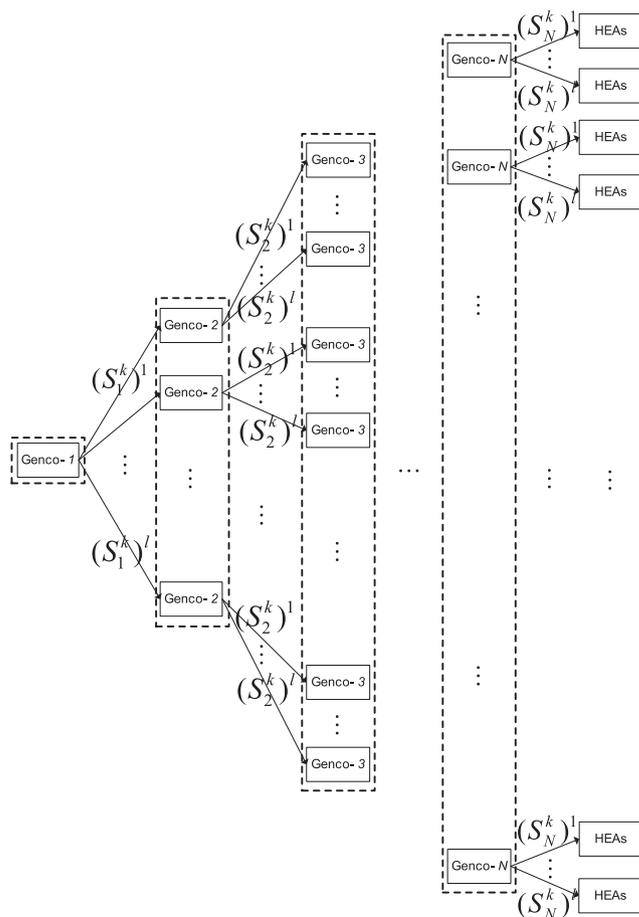


Fig. 2. Extensive form of a subgame at week-k.

the HEA markets, so that the payoffs for week k can be calculated. Fig. 3 represents an entire GMS game, consisting of all subgames within the planning horizon T . The dotted-line boxes indicate the same week in the game. The final payoffs of the strategy profiles are derived by summing the payoffs for the individual weeks.

2.1.3. Strategy and payoff

Each Genco determines its own strategies of whether or not to commit its generating units to maintenance for every week of the scheduling horizon. Afterwards, a strategy profile is constructed by integrating the strategies of all the players. Some strategy profiles related to negative reserve margin should be adjusted by a reliability-centered ISO. Such profiles are then treated as infeasible during the game.

A player's payoff is defined as the sum of the profits of its generating units from the HEA markets over the game horizon. It is calculated by subtracting the sum of the production costs and maintenance costs from the HEA revenues. HEA outcomes are determined only by the GMS of each Genco, since we do not explicitly consider the strategic offering behavior of the individual Gencos. Therefore, the payoff P_i of Genco- i can be indirectly defined as a function of strategy profile S , and is given by

$$P_i(S) = \sum_{k=1}^T \sum_{t=1}^H \sum_{j=1}^{N_i} \left\{ \rho^{k,t}(S) \cdot q_{ij}^{k,t}(S) - f_{ij}^{k,t}(S) - m_{ij} \cdot q_{ij}^{\max} \cdot X_{ij}^k(S) \right\}$$

where $f_{ij}^{k,t}(S) = a_{ij} \cdot (q_{ij}^{k,t}(S))^2 + b_{ij} \cdot (q_{ij}^{k,t}(S)) + c_{ij} \quad \forall i \in N, \forall S \in \mathcal{S}^f$ (1)

where $X_{ij}^k(\cdot)$, $f_{ij}^{k,t}(\cdot)$, $q_{ij}^{k,t}(\cdot)$ and $\rho^{k,t}(\cdot)$ are functions of the strategy profile S . The maintenance period information for each generating unit of Genco- i is implicitly embodied in S . The generation quantity $q_{ij}^{k,t}(\cdot)$ is obtained from the HEA results for each hour. There exist 168 HEAs in a week for each feasible maintenance strategy profile in the markets, throughout the scheduling horizon. The market clearing price $\rho^{k,t}(\cdot)$ is calculated from the offered price of a marginal plant, and is given by

$$\rho^{k,t}(S) = \max_{i \in N, j \in N_i} \left\{ mc_{ij}^{k,t}(S) : q_{ij}^{k,t}(S) > 0 \right\}$$

where $mc_{ij}^{k,t}(S) = 2a_{ij} \cdot (q_{ij}^{k,t}(S)) + b_{ij} \quad \forall k, \forall t, \forall S \in \mathcal{S}^f$ (2)

The set of constraints for Genco- i in the GMS problem is as follows:

$$(1 - X_{ij}^k(S)) \cdot q_{ij}^{\min} \leq q_{ij}^{k,t}(S) \leq (1 - X_{ij}^k(S)) \cdot q_{ij}^{\max} \quad \forall i \in N, \forall j \in N_i, \forall k, \forall t, \forall S \in \mathcal{S}^f$$
 (3)

$$\sum_{k=1}^T X_{ij}^k(S) = W_{ij} \quad \forall i \in N, \forall j \in N_i, \forall S \in \mathcal{S}^f$$
 (4)

$$X_{ij}^k(S) - X_{ij}^{k-1}(S) \leq X_{ij}^{k+W_{ij}-1}(S)$$

s.t. $X_{ij}^k(S) = 0 \quad \forall i \in N, \forall j \in N_i, k \leq 0, k \geq T, \forall S \in \mathcal{S}^f$ (5)

Constraint (3) represents the minimum power output and maximum generating unit capacity. Constraint (4) represents the duration of maintenance. Constraint (5) implies that the maintenance of each unit should not be interrupted once it begins. The corresponding final payoffs are calculated for each strategy profile in accordance with this GMS problem.

2.1.4. Solution

Nash equilibrium is widely considered to be the solution of various forms of games. The concept of subgame perfect (Nash equilibrium) SPNE can be applied to obtain the solution of a dynamic game. In general, a technique of backward induction is used to find the SPNE [22]. The solution profile of Genco- i in this game can then be represented as

$$P_i((S_i^{\text{Nash}})^{\text{tr}} S_{-i}^{\text{Nash}}) \geq P_i((S_i)^{\text{tr}} S_{-i}^{\text{Nash}}) \quad \forall i \in N, \forall S \in \mathcal{S}^f$$
 (6)

Inequality (6) represents the mathematical form of the Nash equilibrium from the perspective of each Genco. The solution profile of all of the Gencos can be obtained by applying the technique of backward induction to (6). Each variable in the function is composed of variable $X_{ij}^k(\cdot)$, a maintenance strategy for generating unit j of Genco- i in week k , although the payoff function of Genco- i in (6) is expressed implicitly. In this game, note that the SPNE obtained by (6) is unique. If there are more than two SPNEs, all Gencos must select one SPNE, which is closer to the reserve criterion, in order to avoid coordination by the ISO.

2.2. Coordination procedure

A reliability-centered ISO estimates a Genco's GMS and determines whether to permit, deny, or adjust the GMS via the coordination procedure. The procedure is decomposed into two distinct steps, one of which is a reliability assessment, and the other is the sending of a rescheduling signal. In the first step, the ISO examines the Genco's GMS in terms of reliability criteria [23], and then makes a decision on whether or not to approve it. If the GMS satisfies the criteria, it is employed as the final schedule without the coordination procedure. Otherwise, the ISO sends a rescheduling signal, requesting that the Genco modify its GMS. The Genco then establishes a modified GMS to comply with the rescheduling signal, and sends the GMS to the ISO. The coordination procedure is repeated until the GMS is approved via the reliability assessment.

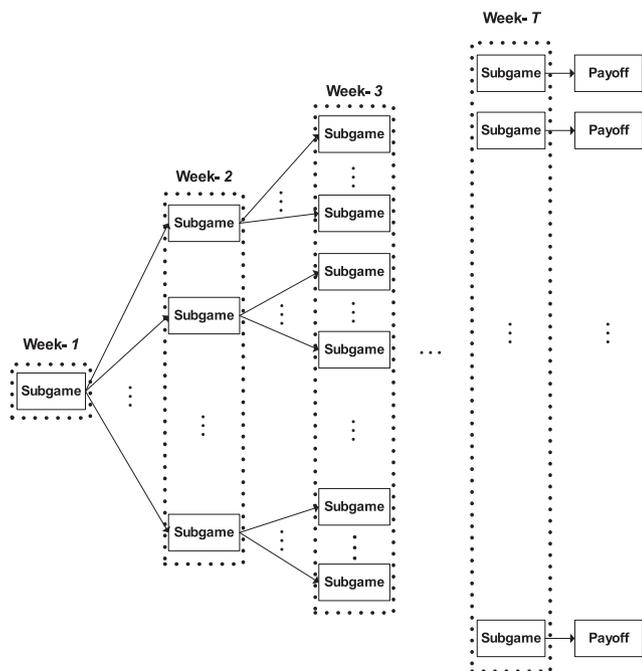


Fig. 3. Extensive form of an entire game.

2.2.1. Reliability assessment

In the coordination procedure, reliability assessments can be divided into two categories. One category employs a stochastic reliability index such as (Expected Energy Not Served) EENS or (Loss of Load Probability) LOLP, while the other utilizes a deterministic reliability index such as an operating reserve [24]. Since the main emphasis of this work is to construct a coordination procedure based on a game-theoretic approach without uncertainties, the latter approach is used for a simple implementation. This implies that uncertainties such as forced outage and demand variation are not taken into account in our study. In this paper, the reserve criterion is adopted for the reliability assessment. The assessment is a checking process that determines whether the hourly calculated reserve is larger than the reserve criterion.

2.2.2. The GMS criteria of ISO

The ISO sets up a GMS criterion to create a rescheduling signal. GMS criteria can be sorted into two classes, contingent upon the objective, which is either leveling the reserve margin or minimizing the operating costs [24]. The former ensures the reserve margin during the planning horizon, while the latter minimizes operating costs such as generating, maintenance, and outage costs. Although the meaning of leveling the reserve margin is implicit in the objective of minimizing the operating costs as a form of outage cost, leveling the reserve margin is adopted as the objective function in our work, since it leads to a more ideal allocation of reserve capacity. Thus, the GMS criterion for reliability assessment is expressed in terms of the objective function for leveling the reserve margin, given by

$$\text{Min} \left\{ \sum_{k=1}^T \sum_{t=1}^H (R_{\text{cal}}^{k,t}(S_{\text{ISO}}))^2 \right\}$$

$$\text{where } R_{\text{cal}}^{k,t}(S_{\text{ISO}}) = \frac{\left(\sum_i^N \sum_j^N q_{ij}^{\text{max}} \cdot (1 - X_{ij}^k(S_{\text{ISO}})) - d^{k,t} \right)}{d^{k,t}} \quad (7)$$

$$R_{\text{cal}}^{k,t}(S_{\text{ISO}}) \geq R_{\text{req}} \quad \forall k, \forall t \quad (8)$$

R_{req} in the reserve criterion constraint (8) is set equal to a constant value within the planning horizon. The maintenance constraints (4) and (5) are also enforced, but are particularized for the ISO. When these constraints are satisfied simultaneously, the ISO's GMS belongs to its feasible strategy set (Here the 'feasible strategy set' should be distinguished from the 'feasible strategy set' of the Genco's GMS).

2.2.3. Rescheduling signal

The basic purpose of a rescheduling signal is to request a Genco's responsibility for insufficient reserve capacity in each period. The rescheduling signal requires a Genco to modify the maintenance period from a period of low reserve margin to a period of high reserve margin by staying close to the objective of leveling the reserve of the ISO. The penalty (incentive) should be imposed upon (provided to) generating units whose maintenance periods are planned when the reserve margin is relatively small (large). The difference between the reserve ratios of the GMS criterion and the Genco's GMS is used to organize the rescheduling signal. This difference for the ν -th iteration is calculated as follows:

$$\delta_{\nu}^{k,t} = \left[R_{\text{Gen},\nu-1}^{k,t} - R_{\text{ISO}}^{k,t} \right] \left| R_{\text{Gen},\nu-1}^{k,t} - R_{\text{ISO}}^{k,t} \right| \quad \forall k, \forall t \quad (9)$$

$$\gamma_{\nu}^{k,t} = \frac{\delta_{\nu}^{k,t} + |\delta_{\nu}^{k,t}|}{\sum_{k=1}^T \sum_{t=1}^H [\delta_{\nu}^{k,t} + |\delta_{\nu}^{k,t}|]} - \frac{|\delta_{\nu}^{k,t}| - \delta_{\nu}^{k,t}}{\sum_{k=1}^T \sum_{t=1}^H [|\delta_{\nu}^{k,t}| - \delta_{\nu}^{k,t}]} \quad \forall k, \forall t \quad (10)$$

The difference $\delta_{\nu}^{k,t}$ in (9) is used as a basis for the rescheduling signal. The weighting factor $\gamma_{\nu}^{k,t}$ in (10) is obtained by normalizing the difference, and the first (second) term of the right-hand side becomes zero if the difference $\delta_{\nu}^{k,t}$ is negative (positive). The left-hand side of (10) can be either negative or positive for each hour t . In order to utilize each $\gamma_{\nu}^{k,t}$ as a weighting factor to determine the incentive or penalty, the sum of the first and second terms is always normalized to 1 or -1, respectively. For example, if the value of $\gamma_{\nu}^{k,t}$ at a specific time is equal to -0.1, 10 percent of the total reserve deficit occurs at this time during the planning horizon T . We then redefine the payoff function of Genco- i as follows:

$$P_{i,\nu}(S) = \sum_{k=1}^T \sum_{t=1}^H \sum_{j=1}^{N_i} \left\{ p^{k,t}(S) \cdot q_{ij}^{k,t}(S) - f_{ij}^{k,t} \left(q_{ij}^{k,t}(S) \right) - m_{ij} \cdot q_{ij}^{\text{max}} \cdot X_{ij}^k(S) + \beta_{\nu} \cdot \gamma_{\nu}^{k,t} \cdot q_{ij}^{\text{max}} \cdot X_{ij}^k(S) \right\} \quad \forall S \in \mathcal{S}^f \quad (11)$$

Here, β_{ν} is an arbitrary value, chosen according to the market environment, and generally selected to minimize the sum of the incentive and penalty. We define the rescheduling signal sent to the Genco as $\beta_{\nu} \cdot \gamma_{\nu}^{k,t}$. If the value of the signal is positive (negative), it implies an incentive (penalty) for the Genco. In our study, the incentive is regarded as the ISO's cost of maintaining system reliability. It should be noted that the incentive/penalty depends on the maximum generation capacity. It is reasonable to impose (provide) a greater penalty (incentive) for a large-capacity generating unit, since its maintenance period directly influences the system reserve capacity at any given time. Using (11), each Genco reschedules its GMS and sends it to the ISO.

3. Solution procedure

Fig. 4 summarizes the GMS process with a coordination procedure based on a rescheduling signal. Generally, it takes time and cost to iteratively conduct the coordination procedure. Here, n is used to restrict the number of iterations of the coordination procedure. The existence of n implies that the coordination procedure could be terminated by the action of ISO before the Genco's GMS is approved as the final plan. The ISO compulsorily alters the Genco's GMS according to its GMS criterion when it does not satisfy the reliability assessment until the maximum iteration number n ; this is called compulsory adjustment.

Step 1) The ISO sets up a GMS criterion using the leveling reserve margin objective throughout the planning horizon.

Step 2) Each individual Genco sets up a GMS with the target of maximizing its own profit, while considering the strategic behavior of the other Gencos. The GMS is then submitted to the ISO.

Step 3) The ISO performs a reliability assessment for the Genco's GMS. If the GMS fulfills the assessment, it is approved as the final GMS for the Genco. Otherwise, the procedure continues to Step 4.

Step 4) The ISO checks the magnitude of the iteration number ν . If it is greater than the maximum iteration number n , the ISO determines the final GMS for the Genco by compulsory adjustment. Otherwise, the procedure continues to Step 5. In practice, the value of n may differ according to market environments [25,26].

Step 5) The ISO creates a rescheduling signal based on the difference between the reserve ratios of the GMS criterion and the Genco's GMS, and sends it to all Gencos.

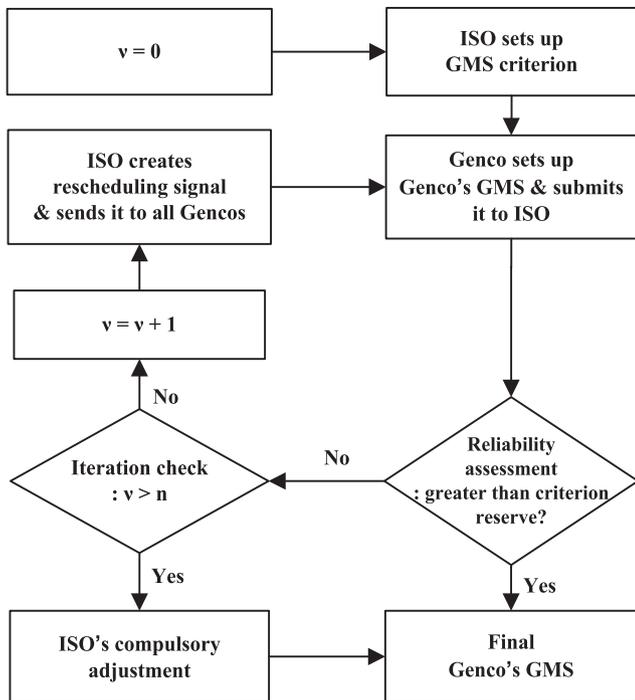


Fig. 4. Proposed GMS process.

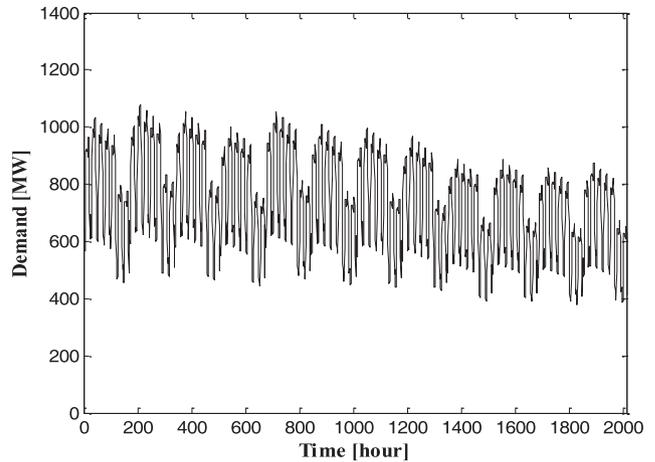


Fig. 5. Hourly peak demand.

Table 2
Weekly peak demand.

Week	1	2	3	4	5	6
Peak demand [MW]	1034	1080	1053	1000	1056	1009
Week	7	8	9	10	11	12
Peak demand [MW]	998	967	888	884	858	872

Step 6) Each Genco sets up a modified GMS containing the rescheduling signal, and submits it to the ISO.

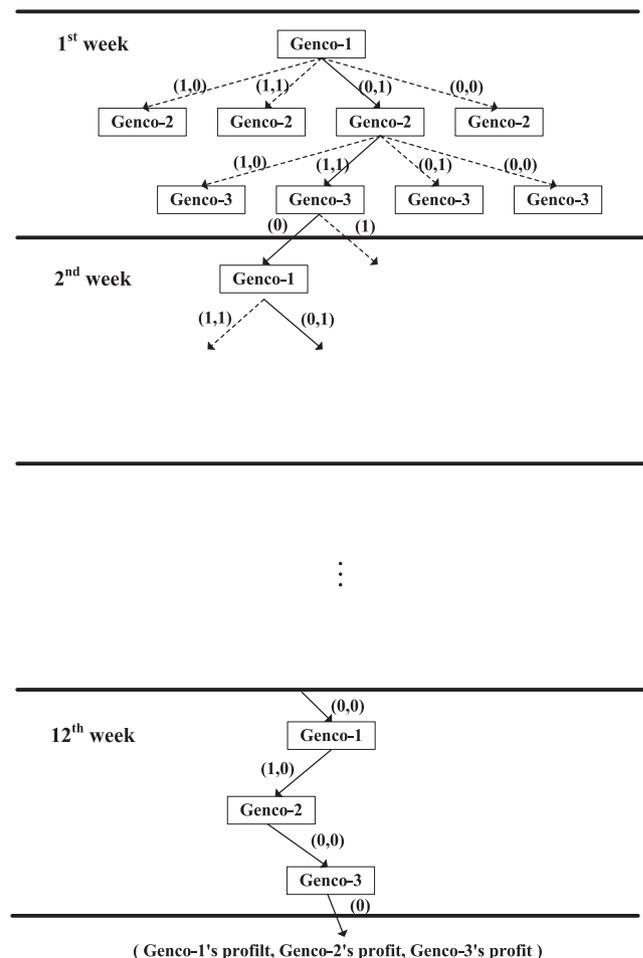
Step 7) The ISO performs a reliability assessment for the modified GMS. If it satisfies the assessment, it is approved as the final GMS. Otherwise, the procedure returns to Step 4.

4. Numerical results

A three-Genco system is used to illustrate the applicability of the proposed approach. Table 1 provides the data for the generating units. The demand profile and weekly peak demand are shown in Fig. 5 and Table 2, respectively. The details of the system can be found in Ref. [27]. Here, n is set equal to 5 to satisfy the convergence criterion. The value of β_v is \$150/MW and the reserve ratio criterion is 10% [28]. Since the planning horizon T is twelve weeks, there are 2016 HEAs. The model is run on a 2.53-GHz dual core processor-based desktop computer using MATLAB R2012a. There are three iterations of the coordination procedure, and the computational time required to attain the final GMS is about 20 min.

According to Table 1, Genco-1 and Genco-2 have two generating units, while Genco-3 has one generating unit. Thus, the maximum number of GMS strategies for each of the three Gencos is 4, 4, and 2, respectively, in each week.

Fig. 6 shows the Genco's decision-making procedure, represented as a game tree for a specific case. The solid arrows represent the possible options for each Genco. The dotted arrows represent the strategic options that are feasible, but not selected. The solid



(Genco-1's profit, Genco-2's profit, Genco-3's profit)

Fig. 6. Game tree of the three-Genco GMS game.

Table 1
Generating unit information.

Genco	Unit	W_{ij}	Max/min [MW]	a_{ij}	b_{ij}	c_{ij}
Genco-1	$g_{1,1}$	2	335/125	0.00221	0.67403	34.287
	$g_{1,2}$	2	232/150	0.00457	0.27216	22.850
Genco-2	$g_{2,1}$	2	260/50	0.00261	1.12134	18.654
	$g_{2,2}$	3	440/160	5E-07	2.32166	19.611
Genco-3	$g_{3,1}$	2	250/130	0.00266	0.71615	17.313

Table 3
Maintenance periods of the Gencos' GMS without a coordination procedure.

Genco	Unit	Maintenance period [weeks]
Genco-1	$g_{1,1}$	11–12
	$g_{1,2}$	11–12
Genco-2	$g_{2,1}$	1–2
	$g_{2,2}$	3–5
Genco-3	$g_{3,1}$	9–10

line denotes the final selection from among the options. The first player, Genco-1, starts by determining the states of its two generating units ($g_{1,1}$, $g_{1,2}$), while at the same time, Genco-2 and Genco-3 determine the states of their units, ($g_{2,1}$, $g_{2,2}$) and ($g_{3,1}$), respectively. In the first week, Genco-1 has four strategies for its own units ($g_{1,1}$, $g_{1,2}$), namely, $[1\ 0]^T$, $[0\ 1]^T$, $[1\ 1]^T$, and $[0\ 0]^T$. In the second week, Genco-1 is able to use two of these four strategies, namely $[1\ 1]^T$ and $[0\ 1]^T$, because the state of ($g_{1,2}$) was specified as “undergoing maintenance” in the previous week. Note that a GMS strategy can be included in the feasible strategy profiles when it satisfies the continuous maintenance constraint. Once the states have been determined by the maintenance strategies for each week, the corresponding final payoffs are assigned to each of the final nodes of

Table 4
Maintenance periods of the GMS criterion.

Genco	Unit	Maintenance period [weeks]
Genco-1	$g_{1,1}$	8–9
	$g_{1,2}$	1–2
Genco-2	$g_{2,1}$	6–7
	$g_{2,2}$	10–12
Genco-3	$g_{3,1}$	3–4

the game tree. The optimal GMS strategy profile is then selected from the feasible strategy set by using the backward induction technique.

Table 3 illustrates the maintenance period results from the optimal GMS strategy profile without a coordination procedure. The maintenance periods of $g_{1,1}$ and $g_{1,2}$ are arranged to maximize the profits during the off-peak periods (11th – 12th weeks, the weeks with relatively lower prices), as shown in Fig. 7. Note that the maintenance period of $g_{2,2}$ (which has the largest capacity) is planned during the 3rd – 5th weeks. In Fig. 8, the reserve ratio is less than 10% in the vicinity of this period. This means that the Genco's GMS does not fulfill the reliability assessment. Thus, the ISO should set up the GMS criterion as a reference for generating a

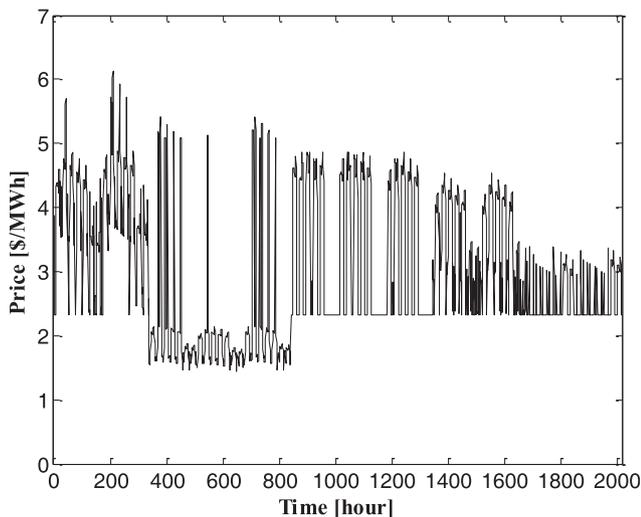


Fig. 7. Market price for the Gencos' GMS without a coordination procedure.

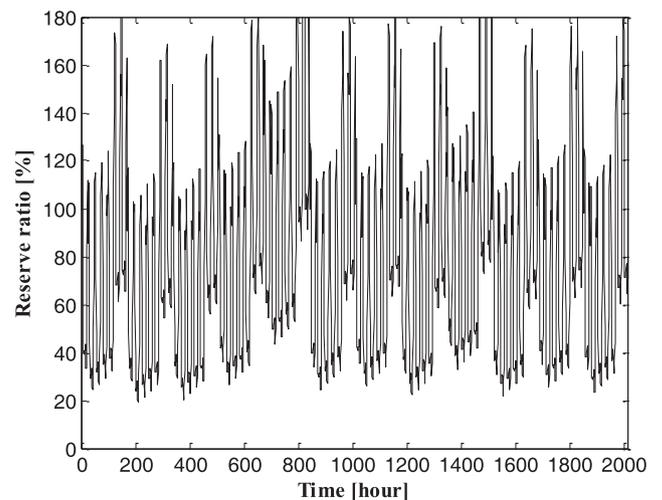


Fig. 9. Reserve ratios via the GMS criterion.

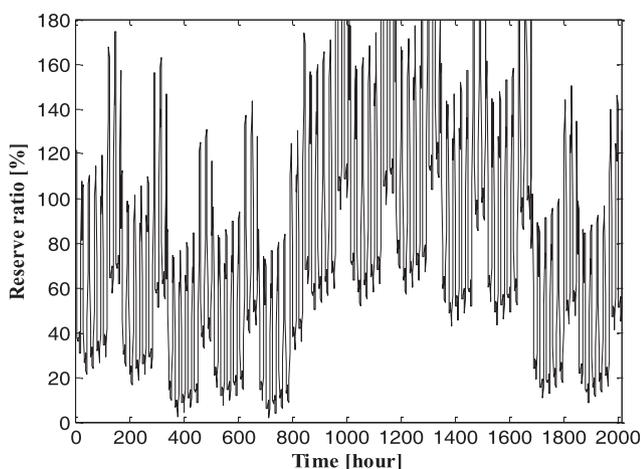


Fig. 8. Reserve ratios of each Genco's GMS without a coordination procedure.

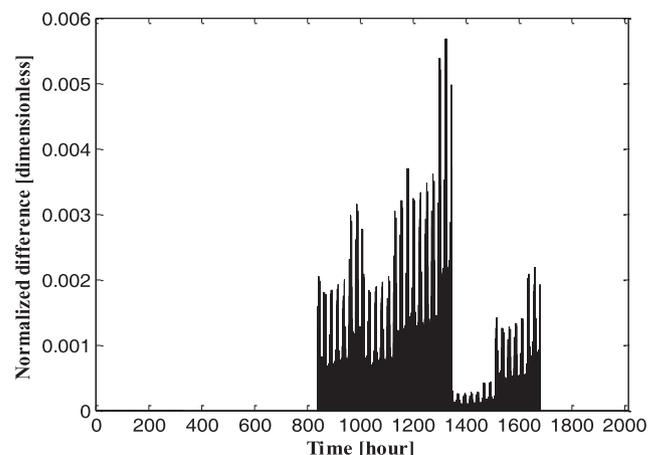


Fig. 10. Normalized differences between the reserve ratios of the Gencos' GMS and the GMS criterion ($\gamma_1^{k,t}$)

Table 5
Maintenance periods of the final GMS with a coordination procedure.

Genco	Unit	Maintenance period [weeks]
Genco-1	$g_{1,1}$	3–4
	$g_{1,2}$	5–6
Genco-2	$g_{2,1}$	1–2
	$g_{2,2}$	10–12
Genco-3	$g_{3,1}$	8–9

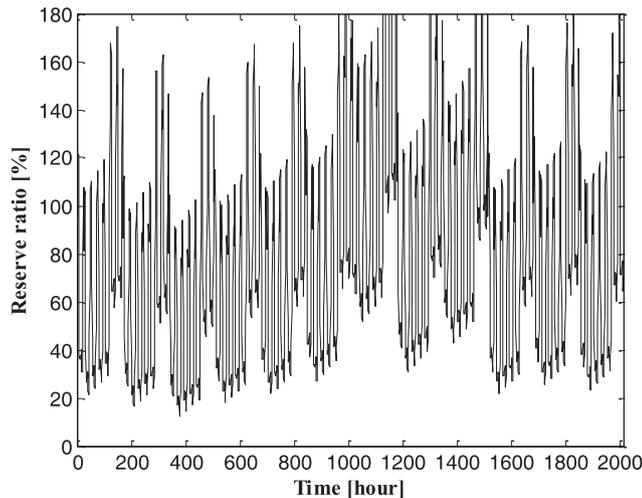


Fig. 11. Reserve ratios of the final GMS with a coordination procedure.

rescheduling signal. At the same time, Table 4 and Fig. 9 show the maintenance periods and reserve ratios, respectively, provided by the GMS criterion. It should be noted that the reserve ratio is maintained at more than 10% during the entire period.

In order to create the rescheduling signal, the ISO computes the difference between the reserve ratios of the Genco's GMS and the GMS criterion. The difference $\gamma_1^{k,t}$ calculated in the first coordination procedure is shown in Fig. 10. All Gencos receive the rescheduling signal $\beta \cdot \gamma_1^{k,t}$, and then resubmit a rescheduled GMS to the ISO based on it. The coordination procedure is repeated until every Genco's GMS satisfies the reliability assessment. In this study, the number of iterations required to attain convergence was 3. The profit-oriented Gencos attempt to select their optimal strategies by compromising between their own GMS and the GMS criterion.

Table 5 lists the maintenance periods obtained using the final GMS of each Genco with a coordination procedure. The maintenance periods of all generating units except $g_{2,1}$ are shifted at least

Table 6
Payoffs with/without a coordination procedure (CP).

Genco	Without CP payoff [\$] (A)	With CP payoff [\$] (B)	Difference [\$] (A–B)
Genco-1	1,594,300	1,592,500	1800
Genco-2	671,200	653,200	18,000
Genco-3	626,900	655,100	–28,200

Table 7
Incentives/penalties and their percentages in the payoffs.

Genco	Incentive/penalty [\$]	Percentage in each payoff
Genco-1	96,338	6.05%
Genco-2	–68,897	10.55%
Genco-3	–33,184	5.07%

one week compared to the case without a coordination procedure. The results show that the periods of all units are evenly distributed over the scheduling horizon to satisfy the reliability assessment. Note that the maintenance period of $g_{2,2}$ is changed to the 10th – 12th weeks, which corresponds to the off-peak periods. Fig. 11 shows the reserve ratios using the final GMS of each Genco; these satisfy the reliability assessment.

Table 6 compares the payoffs for each Genco for both cases (with and without a coordination procedure). Table 7 illustrates the incentive/penalty and its percentage in each payoff. Through the coordination procedure, the payoff for Genco-1 (Genco-3) is decreased (increased), even though it receives the incentive (penalty). On the other hand, the payoff for Genco-2 is reduced after receiving the penalty. As Table 7 indicates, the rescheduling signal acts as either an incentive or a penalty to ensure the reserve margin throughout the planning horizon. Although its percentage is quite small in each payoff, the rescheduling signal is utilized to derive the final GMS while satisfying the Genco and the ISO.

5. Conclusion

A competitive GMS process has been proposed for obtaining an optimal maintenance plan via a coordination procedure in electricity markets. The Genco GMS process was modeled as a non-cooperative dynamic game in order to analyze the strategic behavior of Gencos. The coordination procedure was designed in terms of a reliability assessment and a rescheduling signal to adjust the GMS of noncompliant Gencos. The numerical results for a three-Genco system were used to demonstrate that the final GMS for the Gencos can be determined via the coordination procedure embedded in the game-theoretic framework. The results indicate that the proposed approach produces compatible outcomes for both the Gencos and the ISO in a competitive market environment. In the future, we will study a stochastic approach to the procedure with a sensitivity analysis.

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