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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.

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]
$f_{i,j}^{k,t}(\cdot)$	production cost of generating unit-j of Genco-i at hour-t in week-k [$]
$m_{i,j}(\cdot)$	maintenance cost of generating unit-j of Genco-i [$/MW]
$mc_{i,j}^{k,t}(\cdot)$	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 [$]
$P_{i,\nu}(\cdot)$	payoff of Genco-i for ν-th iteration [$]
$q_{i,j}^{k,t}(\cdot)$	generation quantity allocated to generating unit-j of Genco-i at hour-t [MWh]
$R_{\text{cal}}^{k,t}$	calculated reserve ratio at hour-t in week-k
$R_{\text{Gen},\nu-1}^{k,t}$	calculated reserve ratio by Genco's GMS at hour-t in week-k for ν-1 iteration
$R_{\text{ISO}}^{k,t}$	calculated reserve ratio by ISO's GMS criterion at hour-t in week-k for ν-1 iteration
S	a maintenance strategy profile in planning horizon, which is represented by a matrix $S = [(S_1)^{\text{tr}}(S_2)^{\text{tr}}\cdots(S_T)^{\text{tr}}]$
S_i	a maintenance strategy of Genco-i in planning horizon, which is represented by a matrix $S_i = [(S_i^1)^{\text{tr}}(S_i^2)^{\text{tr}}\cdots(S_i^T)^{\text{tr}}]$
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 $S^k = [S_1^k S_2^k \cdots S_N^k]$
S_i^k	a maintenance strategy of Genco-i in week-k, which is represented by a vector $S_i^k = [X_{i,1}^k X_{i,2}^k \cdots X_{i,N_i}^k]$
$(S_i^k)^1$	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 $S_{-i}^{\text{Nash}} = [(S_1^{\text{Nash}})^{\text{tr}}(S_2^{\text{Nash}})^{\text{tr}}\cdots(S_{i-1}^{\text{Nash}})^{\text{tr}}\cdots \times (S_{i+1}^{\text{Nash}})^{\text{tr}}\cdots(S_N^{\text{Nash}})^{\text{tr}}]$
$X_{i,j}^k(\cdot)$	a maintenance strategy of generating unit-j of Genco-i in week-k (unit on maintenance = 1, otherwise = 0)
$\gamma_\nu^{k,t}$	weighting factor for calculating incentive (or penalty) at time-t in week-k for ν-th iteration
$\delta_\nu^{k,t}$	difference of reserve ratio between GMS criterion and Genco's GMS at time-t in week-k for ν-th iteration
$\rho^{k,t}(\cdot)$	market clearing price at time-t in week-k [$/MWh]

Constants

$a_{i,j}$	quadratic coefficient of generation cost [MWh²/$]
$b_{i,j}$	linear coefficient of generation cost [MWh/$]
$c_{i,j}$	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
$q_{i,j}^{\max}$	maximum capacity of generating unit-j of Genco-i [MW]
$q_{i,j}^{\min}$	minimum power output of generating unit-j of Genco-i [MW]
R_{req}	reserve ratio criterion (or required reserve ratio)
T	planning horizon [week]
$W_{i,j}$	duration of maintenance for generating unit-j of Genco-i [week]
$ß_\nu$	coefficient for calculating incentive (or penalty) for ν iteration[$/MW]

Indices

i	Gencos
j	generating units of a Genco
k	week
t	time (in this work, a time represents a hour)
ν	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.