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Determination of Secondary Reserve Requirement Through Interaction-dependent Clearance Between Ex-ante and Ex-post

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Abstract – This paper discusses a method for the determination of frequency control reserve requirement with consideration of the interaction between ex-ante planning and real-time balancing. In proposed method, we consider the fact that the delivered energy for tertiary control reserve is determined based on required capacity for secondary control reserve and the expected amount of load errors. Uncertain load errors are derived by Brownian motion, an optimization method is suggested using a stochastic programming. In a short, we propose an interactive dependent method for determining secondary control reserve requirement based on the principle that it satisfies to minimize the total cost. As a result, this paper provides will analyze for an example model to demonstrate the capabilities of the method.

Keywords: Ancillary service, Frequency control reserve, Primary control reserve, Secondary control reserve, Tertiary control reserve, Real time balancing , Stochastic programming, Market settlement

1. Introduction

The essential prerequisite for stable and reliable operation of the electrical power system is to maintain a balance between the generation and load at all time. Conventionally, frequency control for real-time power balancing is implemented by directly handling centralized, integrated utility [1-4]. However, one of major changes driven by deregulation in electric power sector is to treat frequency control as commodities. These are called frequency control reserves (FCRs) as an essential part of ancillary services (AS), consist of primary control reserve, secondary control reserve and tertiary control reserve based on a framework in Union for the Co-ordination of Transmission of Electricity (UCTE), which is the major portion of the European Network of Transmission System Operators for Electricity (ENTSO-E). These reserve services are generally procured through a market mechanism [1, 4-6].

There are lots of literatures dealing with FCRs problems, which generally can be categorized into three types. One of research themes is energy and FCR scheduling problem by the system operator (SO). This problem is about market auctions for trading of energy and FCRs. There are two forms of auctions in energy and FCR scheduling in the deregulated electricity market. The first method adopts a sequential reserve procurement approach which decides the quantity of each reserve in a series of auctions [7-18]. Although this approach has an advantage in the computational aspect, experience has shown that the model may lead to quite undesirable situation due to price reversal problem or the probability of reserve capacity insufficient, illustrated by the failure of the California FCR market at the end of the 1990s [11]. The second method is a simultaneous auction of energy and FCR to overcome this price reversal problem. This approach currently is used at the New York Independent System Operator (ISO) and New England ISO. Another research theme is bidding problems for energy and FCR. From the view of suppliers, energy market and reserve market are interdependent due to each generating resource's capacity limit and technical aspect. This problem is about a decision making problem to achieve total benefit maximization [19-23]. Decision support for bidding has been studied using deterministic and stochastic approaches to deal with unknown market prices [21]. The other research theme is a problem to determine FCR requirements. Most of the current research on this problem assumes that the requirement of reserves is predetermined, which means that there is no need to consider short-term uncertainty in real time. In practice, according to a grid code such as UCTE operation book, FCR requirement is pre-determined as quantities based on some reliability criteria without in the consideration of coupling relationship in economic aspects between pre-operation and post-operation phase [11-13, 17, 18].

In this paper, we will focus on the issue of establishment of secondary control reserve requirement in the consideration of coupling relationship between ex-ante planning and real-time balancing through reserves activation. This approach determines the capacity of secondary control reserve that minimizes the total cost of holding and utilizing secondary and tertiary control reserve. The organization of the reminder is as follows. Section 2 describes a process of planning, operation, and settlement

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for FCR in the competitive market. Section 3 presents the optimization framework that allows deriving an optimal determination method of secondary reserve capacity. Section 4 is a detailed case study where results are reported and analyzed. Some relevant conclusions are drawn in Section 5.

2. Ancillary Service Market

As the definition and classification of FCRs differ from a country to another, it is required to investigate how to define FCR in different product according to various countries and technical roles. There is no standard definition of the AS globally accepted [3, 15, 24]. This section outlines a framework that can accommodate definitions for FCRs without confusion because of difference defined in two different criteria. We classify FCR for frequency control that are currently used in UCTE, and compare the name of reserves defined by North American Electric Reliability Council (NERC). Then we describe the principle for real-time balancing and market clearing process.

2.1 Frequency control reserve definition and classify-cation

An appropriate real time balancing between load and generation depends on the available FCRs. Its adequate planning for each reserve therefore is an important task for the ISO. FCRs can be classified into three levels based on the time scale separation principle: primary, secondary and tertiary frequency control reserves as depicted in Fig. 1 [24, 26]. This figure explains three sequential phase in frequency control. Primary control reserve stabilizes frequency deviation within a few short seconds. It acts as a proportional controller that restrains large frequency errors. Due to the proportional structure of primary control, frequency error still remains as quasi-steady states. Secondary control reserve takes over a linear combination of the frequency deviation and tie-line electrical power exchange known as Area Control Error (ACE). The main purpose of secondary control is to eliminate the ACE to zero within some minutes. Tertiary control replaces secondary control, based on an economic generation dispatch that reschedules the set point of generating units. In the event of incessant deviation and in order to free up secondary control reserves, ISO manually activates tertiary control reserve through Economic Dispatch (ED) program running at the control center [3, 7, 16, 24, 26].

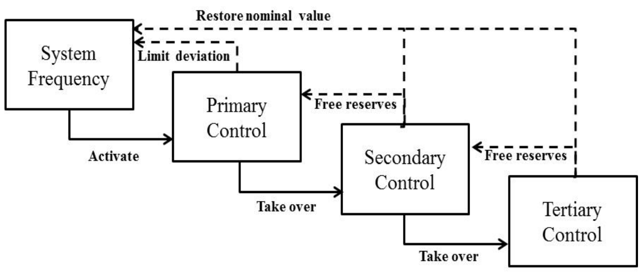

Fig. 1. Frequency control mechanism in UCTE region

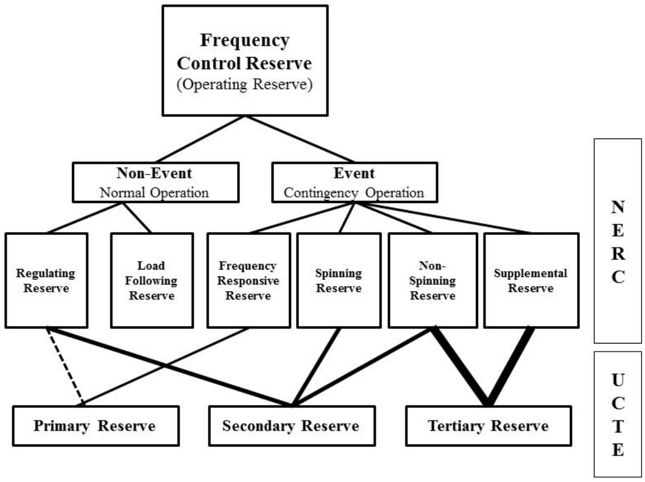

Fig. 2. Frequency control reserve categories

Fig. 2 explains how FCR types classify and compares the difference between NERC and UCTE policies. A main difference between NERC and UCTE is that NERC separates FCRs into non-event reserve and event reserve, whereas UCTE does not [26]. Non-event means continuous small deviation considered as normal conditions and happened continuously. Events are infrequent things that are more severe than in normal conditions. NERC uses the term contingency reserve to highlight severe situation such as unexpected failure, large error of load forecasting.

Spinning reserve is generally defined as extra amount of generating capacity, synchronized with the grid, and ready to serve additional demand. Non-spinning reserve is generating reserve, not connected but able to be synchronized within a specified time. However NERC uses the term spinning reserve or non-spinning reserve to refer to secondary control reserve under contingency reserve. Supplement reserve is defined as tertiary reserve under contingency. Regulating reserve under non-event in NERC classification only can be translated to secondary reserve, however, both primary and secondary reserve take cover a role of regulating reserve in UCTE area. Load following is the action to follow expected load pattern as a part of optimal dispatch, only separately considered in NERC [7, 26]. However, tertiary control reserve takes a role as load following. In this paper, to avoid confusion, we follow the terms defined by UCTE.

2.2 Process of FCR planning in Pre-operation phase

There are various market structures to procure FCR. However, we only consider a pool market for FCRs through centralized auction. Other market structures such as a bilateral market are not our research scope. Since load

Table 1. Remuneration structure in different countries

Reserve services	Capacity	Energy	Mandatory
Primary control	France,	U.K	PJM
Secondary control	France	France, PJM	
Tertiary control	France,	France, Germany,	

changes instantaneously, it is essential that ex-ante markets secure enough reserves associated with real time operation. The important characteristic of FCR in this paper is that capacity is reserved and procured ahead and then incremental or decremental energy is activated in response to real time imbalance between expected energy and load. This means that FCRs are different from other power products in that they are paid for availability, whether or not they are dispatched. Of course, if they dispatch based on auto or manual request in real time, delivered energy is remunerated.

In a short, there are two kinds of prices in FCR markets to be paid to participants with generating resources. One is the price paid for reserved capacity availability and the other is the price for delivered energy that is activated under specific conditions. However, there are different structures of remuneration for FCRs as illustrated Table 1 [2].

In this paper, we follow the structure of settlement in PJM and Spain. It means that the provision of primary reserve is a mandatory, non-paid service. Therefore, primary reserve dose not influence the FCRs operation cost. Apart from primary reserve, secondary reserve is remunerated as market products settled by its availability based on the capacity in ex-ante market. Tertiary reserve providers are compensated for both availability and utilization. Moreover, we consider separate auctions for each category of reserve (secondary reserve capacity, tertiary reserve capacity and tertiary reserve delivered energy). The bids for each reserve service are arranged in price order to form an increasing staircase for each operating hour. We assume that capacity prices are determined in accordance with the most expensive bid taken by ISO as a single buyer every 15 minutes. Bid curves for each reserve in ex-ante market are illustrated in Fig. 3. In this paper, we assume that the size of positive and

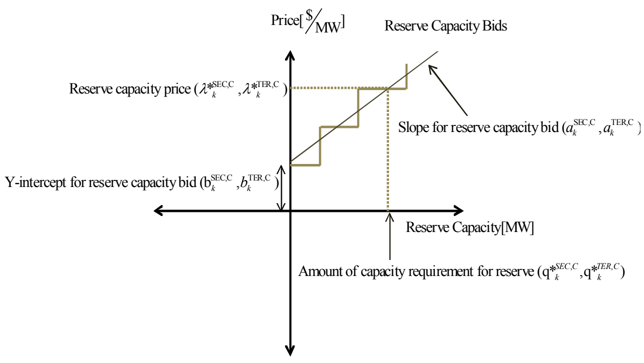

Fig. 3. Reserve capacity bids in day-ahead market

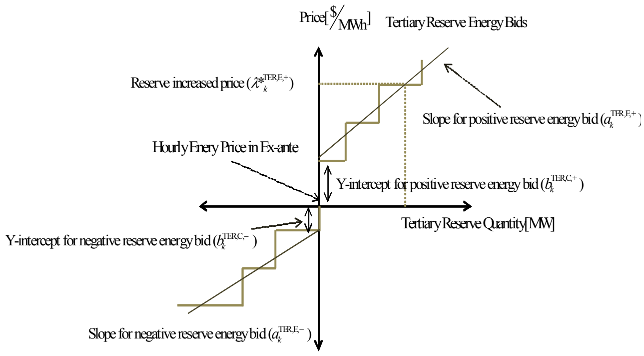

Fig. 4. Up/down reserve energy bids in real-time market

negative capacity is same.

The SO clears the reserve capacity markets based on the submitted bids with a 15 minutes time basis. However, the method of auction for utilized quantities of tertiary control reserve is linked with real-time price, usually settled at ex-post, i.e. the real time price at the time of energy delivery is uncertain for market participants as depicted in Fig. 4

2.3 Continuous adjustment in real-time operation

As explained in section 2.1, primary control reserve stabilizes frequency almost immediately following the disturbance. Secondary control reserve is deployed through automatic generation control (AGC) to release primary control reserve within some minutes. Tertiary control reserve is supervisory with respect to secondary control, refers to manual changes in the dispatching of generating units and load to free up secondary control reserve. Operation and settlement rules for provision of FCRs are well defined in many literatures including grid codes. In contrast, grid codes like UCTE operation handbook, FERC Order 888 do not describe definitive and unambiguous methods for implementing of tertiary control reserve. As a consequence, different methods have been applied to execute tertiary control reserve without standards. Methods may be a control by heuristic or probabilistic method. According to previous studies and practices, tertiary reserve activation is generally depends on the utilized level of secondary reserve [27, 28]. Therefore, we assume that execution of tertiary control reserve is based on a specific level of secondary control reserve, considering time delay and load deviation pattern. In this assumption, capacity requirement of secondary control reserves is referred to as the bandwidth of secondary control. If the secondary reserve meets its limits of the bandwidth defined as saturation, it jeopardizes the system security. To keep power system stable, ISO must activate tertiary control to relieve secondary control reserve before saturation [29]. When secondary control reserve meet certain level of its capacity, ISO calls tertiary reserve to release amount of required energy in the consideration of time delaying characteristics of tertiary reserve. In this paper, amount of activated tertiary reserve is determined on the value of the integer multiples of certain level of secondary reserve as a following equation (1).

$$q_k^{SEC,C} = \chi q_k^{SEC,C,contract} \tag{1}$$

Here, $q_k^{SEC,C,contract}$ is contracted quantity to determine the relevant price in the day-ahead market, and q_k^{SEC} is a value of the bandwidth as an activation point of tertiary reserve. In this paper, we set the weight value χ to 1 based on the value for a simple optimization problem without considering delay time of tertiary reserve. The delivered energy for tertiary control reserve is determined based on the scheduled quantities for secondary control reserve and load fluctuation. For example, if large amount capacity of secondary control reserve is scheduled in the pre-operation phase, SO may save more during real-time operation with tertiary reserve utilization.

3. Methodology

In this chapter, we make mathematical formulations to describe real time balancing with several reserves. Then, we suggest an optimization framework to determine secondary reserve requirement considering the interaction between the day ahead and the real time operation.

3.1 Real time balancing equations

Demand error, $q^D_{k,t}$, means imbalances of load and generation mainly given by power plant outages, load oscillations, load forecast errors and changes in exchanges schedule [2]. Demand errors are recovered by secondary and tertiary reserve utilization, as follow

$$q_{k,t}^{D} = q_{k,t}^{SEC,L} + q_{k,t}^{TER,L} \tag{2}$$

$$q_{k,t}^{SEC,L} = (\alpha_{k,t} - \beta_{k,t}) q_k^{SEC,C} \tag{3}$$

$$q_{k,t}^{TER,L} = q_{k,t-1}^{SEC,L} + \beta_{k,t} q_k^{SEC,C} \tag{4}$$

subject to

$$\alpha_{k,t} = \begin{cases} 0 & if\ t = 0 \\ \dfrac{\Delta q_{k,t}^{D} + q_{k,t-1}^{SEC,L}}{q_k^{SEC,C}} & otherwise \end{cases} \tag{5}$$

$$\beta_{k,t} = \begin{cases} \lfloor \alpha_{k,t} \rfloor & if\ \alpha_{k,t} \geq 0 \\ \lceil \alpha_{k,t} \rceil & otherwise \end{cases} \tag{6}$$

Demand error is eliminated by secondary and tertiary reserves according to amount of error and current level of secondary control reserve. If secondary reserve meets its limit (capacity), tertiary reserve is released by amount of secondary capacity to free up saturation of secondary reserve. Therefore, tertiary reserve is activated based on integer multiples ($\beta_{k,t}$) of secondary reserve. The delivered energy for tertiary reserve can be calculated as following equation. $\beta_{k,t}$ is related to the activated quantity based on demand error, degree of saturation of the bandwidth. Positive value of $\beta_{k,t}$ is positive adjustment of tertiary reserve, on the other hand, its negative value means negative adjustment of tertiary reserve.

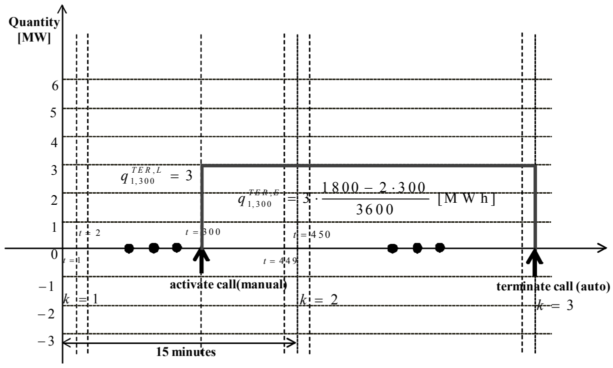

Fig. 5. Example of tertiary reserve energy adjustment

$$q_{k,t}^{TER,E} = \beta_{k,t} q_k^{SEC,C} \frac{T - 2t}{2T} \tag{7}$$

Here, t is the time index based on 2 seconds and T is a settlement period. We set T to 30 minutes (1800 seconds), 2T is 3200 seconds which means 1 hour used for scaling MWh value. We assume that activated tertiary reserve should be continued for at least 15 minutes, terminated in end of next time index k. Fig. 5 shows a simple example to illustrate equation (7).

3.2 Market settlement process in pre and post operation phase

In this paper, we consider coupling between ex-ante and ex-post reserve markets. In detail, we focus on the problem with day-ahead capacity acquisition and real-time adjustment which relate to procuring secondary and tertiary reserves. Capacity prices for secondary, tertiary reserve are formulated as follows,

$$\lambda_k^{SEC,C} = a_k^{SEC,C} q_k^{SEC,C} + b_k^{SEC,C} \tag{8}$$

$$\lambda_k^{TER,C} = a_k^{TER,C} q_k^{TER,C} + b_k^{TER,C} \tag{9}$$

During settlement time duration k (15 minutes), demand errors are detected every frequency control signal time t (2 seconds). To remove demand errors, appropriate secondary and tertiary reserve is utilized every time index t. Therefore, the settlement price for tertiary delivered energy during time period k is divided into 3 cases according to the values of as following equations.

$$n_{k,0}^{+} = n_{k,0}^{-} = 0 \tag{10}$$

Beginning of each stage, the number of calling tertiary reserve is initialized to 0 (10). Every time the SO calls tertiary reserve, $n^{+}_{k,0}$ (positive order) or $n^{-}_{k,0}$ (negative order) is cumulative according to each activation order. Price for delivered energy of tertiary reserve is determined to compensate a caused imbalance when the SO activates tertiary reserve in real time.

Case 1: $\beta_{k,t} > 0$

$$\lambda_{k,t}^{TER,inc,E} = a^{+} n_{k,t}^{+} q_{k}^{SEC,C} + b^{+} \tag{11}$$

$$\lambda_{k}^{TER,C} = a_{k}^{TER,C} q_{k}^{TER,C} + b_{k}^{TER,C} \tag{12}$$

subject to

$$n_{k,t}^{+} = n_{k,t-1}^{+} + \beta_{k,t} \tag{13}$$

$$n_{k,t}^{-} = n_{k,t-1}^{-} \tag{14}$$

Case 2: $\beta_{k,t} < 0$

$$\lambda_{k,t}^{TER,inc,E} = 0 \tag{15}$$

$$\lambda_{k,t}^{TER,dec,E} = -a^{-} n_{k,t}^{-} q_{k}^{SEC,C} + b^{-} \tag{16}$$

subject to

$$n_{k,t}^{+} = n_{k,t-1}^{+} \tag{17}$$

$$n_{k,t}^{-} = n_{k,t-1}^{-} - \beta_{k,t} \tag{18}$$

Case 3: $\beta_{k,t} = 0$

$$\lambda_{k,t}^{TER,inc,E} = 0 \tag{19}$$

$$\lambda_{k,t}^{TER,dec,E} = -a^{-} n_{k,t}^{-} q_{k}^{SEC,C} + b^{-} \tag{20}$$

subject to

$$n_{k,t}^{+} = n_{k,t-1}^{+} \tag{21}$$

$$n_{k,t}^{-} = n_{k,t-1}^{-} \tag{22}$$

As describe above, settlement price for real-time balancing through tertiary control reserve is formulated as follows:

$$\lambda_{k,t}^{TER,E} = \begin{bmatrix} \lambda_{T}^{energy} + \lambda_{k,t}^{TER,inc,E} & if\, \beta_{k,t} > 0 \\ \lambda_{T}^{energy} - \lambda_{k,t}^{TER,dec,E} & otherwise \end{bmatrix} \tag{23}$$

Cost of each reserve from the SO's view can be calculated from following equations.

$$C_{k}^{SEC,C} = \lambda_{k}^{SEC,C} q_{k}^{SEC,C} \tag{24}$$

$$C_{k}^{TER,C} = \lambda_{k}^{TER,C} q_{k}^{TER,C} \tag{25}$$

$$C_{k}^{TER,E} = \lambda_{k}^{TER,E} q_{k}^{TER,E} \tag{26}$$

$$C_{k}^{Reserve,Total} = C_{k}^{SEC,C} + C_{k}^{TER,C} + C_{k}^{TER,E} \tag{27}$$

Therefore, the objective function during time index (1 hour) is expressed as the following.

$$\min_{q_k^{SEC,C},\, q_k^{TER,C}} \sum_{k=1}^{4} C_{k}^{Reserve,Total} \tag{28}$$

3.3 Demand error model

In the frequency control market, uncertain demand fluctuations are the main factor which determines the reserve provision cost through the ex-post market settlement. We define demand error as power imbalance in the real time operation phase. In this paper, we use the term demand errors as real-time imbalance to affect the provision schedule of secondary and tertiary reserves. We describe demand errors as a mean-reverting process known as an Ornstein-Uhlenbeck process as below. This process, although satisfying the Markov property, does not have independent increments. We consider the demand errors as a relevant state variable, and model it as a mean-reverting process with drift [30]-[32]. By changing each parameter based on operational condition, various demand model can be tested.

$$\Delta q_{k,t}^{D} = \eta(\overline{q}_{k}^{D} - q_{k,t-1}^{D})\Delta t + \sigma_{k} \varepsilon_{t} \sqrt{\Delta t} \tag{29}$$

Here, η is the speed of reversion, $\overline{q}$ is the mean value of q^{D}_{t}, ε is normally distributed with mean zero and σ is instantaneous standard deviation of this process.

3.4 Stochastic programming framework

We use the stochastic programming (SP) based methods for distributed decision marking under uncertainties. SP is used to formulate and solve a problem with uncertain load errors. In particular, the types of decisions of interest are to find optimal scheduling for secondary reserve capacity in ex-ante considering relevant amount of delivered energy of tertiary reserve in ex-post clearance procedure. The overall objective is to optimize expected performance; this is done in an interactive way, since the strategy for markets operation for the delivery of frequency control is adapting as more information is gained in real-time about the uncertainty. In this paper, we adopt the dynamic programming (DP) backward algorithm to calculate the expected total reserve cost at time k, translated as a stage [31, 32]. DP framework is illustrated in Fig. 4. In the DP framework, we define as:

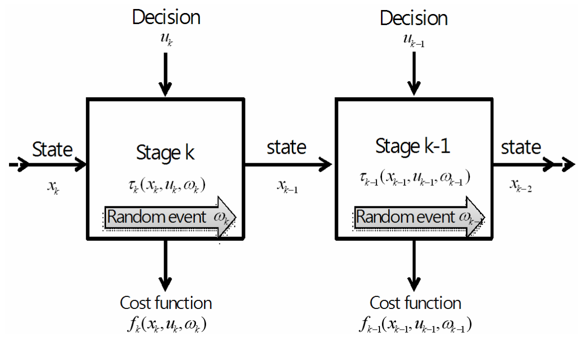

Fig. 6. DP framework for discrete finite state problem

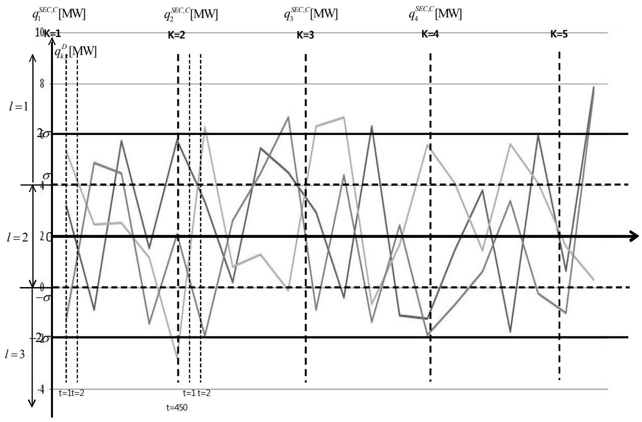

Fig. 7. 3 States model for SP framework

1. State variable, x_k, is q_k^D at time index k.
2. Decision variable, u_k, is $q_k^{SEC,C}$ at time index k.
3. Random variable, w_k, is $q_k^{TER,E}$ during the period k.

In this paper, we divide the system state at each stage into 3 states based on the value given from PJM, illustrated in Fig. 5. Then, we generate 10000 Monte Carlo samples of the demand errors models to estimate transition probability at each state in each stage. Variable l_k means a position of demand errors at stage k, which describes a discrete state in SP framework as described a following equation. State at stage k, x_k is described as l_k.

$$l_k = \begin{cases} 1, \; if \; q_k^D > \sigma \\ 2, \; if -\sigma \le q_k^D \le \sigma \\ 3, \; if \; q_k^D < -\sigma \end{cases} \tag{30}$$

4. Case Study

This section provides the simulation results of applying the proposed technique using stochastic programming as an optimization on the base of the daily demand error data from Korea electricity market to generate demand models. Simulation assumptions and parameters are described in Table 4. Moreover, we assume that each reserve requirements vary throughout a day but remain fixed during 15 minutes period (stage k). In these case studies, we are comparing the dynamic reserve requirement determination method (proposed method) and the static reserve requirement determination method (traditional method). Tables 5-7 show different provision schedules depending on various speed of reversion, η = 0.0, 0.2 and 0.5 to test various demand model scenarios.

Table 8 compares the total reserve cost between the proposed model and the previous method. This illustrates that the determination method for secondary reserves

Table 4. Parameters used in case study

Input variable	Value
$a_k^{SEC,C}$	0.03
$a_k^{TER,C}$	0.005
$a_k^{TER,E,+}$	0.01
$a_k^{TER,E,-}$	0.01
$b_k^{SEC,C}$	3
$b_k^{TER,C}$	2
$b_k^{TER,E+}$	2
$b_k^{TER,E-}$	-2
$q_k^{TER,C}$	800
σ	183.2
μ	0.176

Table 5. Provision schedule for secondary control reserve capacity ($\eta = 0$)

Stage k	1	2	3	4
1	-	324	344	341
2	320[MW]	326	334	317
3	-	332	330	342

Table 6. Provision schedule for secondary control reserve capacity ($\eta = 0.2$)

Stage k	1	2	3	4
1	-	314	329	321
2	310[MW]	323	327	323
3	-	329	331	342

Table 7. Provision schedule for secondary control reserve capacity ($\eta = 0.5$)

Stage k	1	2	3	4
1	-	296	305	311
2	290[MW]	302	315	305
3	-	299	312	322

Table 8. Comparison between dynamic and static provision methods

η_T	Interactive Method	Static Method		
		300[MW]	350	400
0.0	15,862 [$]	22,340	21,125	20,431
0.2	13,251	19,432	18,515	21,124
0.5	12,421	17,821	21,621	22,450

requirement with consideration of interaction between ex-ante and ex-post markets shows lower reserve cost than determination methods through pre-determined reserve capacity without consideration of interaction between day-ahead reserve market and real time balancing.

5. Conclusion

In this paper a new decision model for secondary reserve capacity is presented with the following characteristics:

1. Incorporation of capacity requirement of secondary reserve in ex-ante and delivered energy of tertiary reserve in ex-post market settlement
2. Comparison between the dynamic and static determination of secondary reserves capacity approaches
3. Allowance of testing several demand errors models in order to apply a demand model closed to actual demand
4. Provision of detailed results for SO in terms of optimal decision and costs

We show that capacity requirement of secondary in day-ahead market and the delivered energy of tertiary control reserve in real time are physically and economically linked. Moreover, this paper supposes a determination method for secondary reserve capacity considering coupling between pre and post-operation. Proposed dynamic determination method shows more economical efficiency than the traditional method. Simulated results in this paper provide some insights about determining reserve capacity in a different view.

Nomenclature

t	The time index for frequency control signal, (2 seconds)
k	The time index for reserves schedule, (15 minutes)
T	The time index for hourly energy schedule, (1 hour)
λ_T^{energy}	Price for hourly scheduled energy, [$/MW]
$\lambda_k^{SEC,C}$	Price for secondary reserve capacity, [$/MW]
$\lambda_k^{TER,C}$	Price for tertiary reserve capacity, [$/MW]
$\lambda_{k,t}^{TER,inc,E}$	Increased price for tertiary reserve energy, [$/MWh]
$\lambda_{k,t}^{TER,dec,E}$	Decreased price for tertiary reserve energy, [$/MWh]
$\lambda_{k,t}^{TER,E}$	Price for tertiary reserve delivered energy, [$/MWh]
$q_{k,t}^{D}$	Quantity of demand errors, [MW]
$q_k^{SEC,C}$	Quantity of secondary reserve capacity, [MW]
$q_k^{TER,C}$	Quantity of tertiary reserve capacity, [MW]
$q_{k,t}^{SEC,L}$	Level of secondary reserve at time index (k, t), [MW]
$q_{k,t}^{TER,L}$	Level of tertiary reserve at time index (k, t), [MW]
$q_{k,t}^{TER,E}$	Quantity of tertiary reserve delivered energy at time index (k, t), [MWh]
$C_k^{SEC,C}$	Cost of secondary reserve capacity at time k, [$]
$C_k^{TER,C}$	Cost of tertiary reserve capacity at time k, [$]
$C_k^{TER,E}$	Cost of tertiary reserve delivered energy at time k, [$]
$C_k^{Reserve,Total}$	Total cost of frequency control at time k, [$]
$n_{k,t}^{+}$	The cumulated number of tertiary reserve positive activation at time index (k, t)
$n_{k,t}^{-}$	The cumulated number of tertiary reserve negative activation at time index (k, t)
$a_k^{SEC,C}$	Slope for secondary reserve capacity bid curve, [$/MW]
$a_k^{TER,C}$	Slope for tertiary reserve capacity bid curve, [$/MW]
$a_k^{TER,E,+}$	Slope for tertiary reserve energy bid curve (positive adjustment part), [$/MWh]
$a_k^{TER,E,-}$	Slope for tertiary reserve energy bid curve (negative adjustment part), [$/MWh]
$b_k^{SEC,C}$	Y-intercept for secondary reserve capacity bid curve, [$]
$b_k^{TER,C}$	Y-intercept for tertiary reserve capacity bid curve, [$]
$b_k^{TER,E+}$	Y-intercept for tertiary reserve energy bid curve (positive adjustment part), [$]
$b_k^{TER,E,-}$	Y-intercept for tertiary reserve energy bid curve (negative adjustment part), [$]
σ	Standard deviation value for load errors , [MW]
μ	Mean value for demand errors, [MW]
η_T	Speed of reversion for demand error model [0~1]
x_k	State variable in DP framework
u_k	Decision variable in DP framework
w_k	Random variable in DP framework
$f_k(x_k, u_k, \omega_k)$	Cost function in DP framework
$\tau_k(x_k, u_k, \omega_k)$	State transition function in DP framework
$Pr_k(x_{k-1} \vert u_k, \omega_k)$	Transition probability distribution in DP framework
l_k	The state at the stage k in DR framework

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