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Design of performance-based frequency regulation market and its implementations in real-time operation

Zhongwei Wang [a,*], Jin Zhong [a,b], Jianhui Li [c]

[a] Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong Special Administrative Region
[b] Luleå University of Technology, Sweden
[c] Guangdong Power Dispatch Centre, Guangzhou, China

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ABSTRACT

The importance of the performance of frequency regulation has already been acknowledged by regulators and Independent System Operators (ISOs). A performance-based frequency regulation market model considering both regulation capacity and regulation mileage constraints is proposed in this paper. In the proposed market, high-performance regulation resources have higher priorities to be selected in the market. Market clearing prices are derived with Lagrange relaxation. The analysis of the components of market clearing prices accurately indicates the correlation between regulation capacity and regulation mileage. To accommodate the proposed regulation market design, AGC allocation algorithm is adjusted based on the market clearing results. The clearing procedure of the market model is demonstrated on an illustrative case. The proposed market design is tested and verified with market simulations and system dynamic simulations. Simulation results are discussed and compared to show the effectiveness of the proposed market design.

1. Introduction

Frequency regulation service plays an important role in power system operation for its real-time balancing of electricity supply and demand. In a deregulated system, frequency regulations are procured through ancillary service markets [1]. In the United States, the independent system operator (ISO) clears energy market and ancillary service market simultaneously, determining the energy schedule and regulation capacity for each resource, as well as the energy clearing price and regulation market clearing price [2–4]. In the Nordic system, a major part of frequency regulation service is settled by long-term bilateral contracts and the rest portion is procured in a merit-order based balancing market [5]. During the past few decades, the increasing penetration of intermittent renewable energy generations, including wind and solar energy, introduces more uncertainties to power system operation, increasing the need for fast ramping regulation resources [6,7] to provide frequency control. Emerging energy storage technologies, such as battery and flywheel energy storage, are ideal regulation resources due to their fast responding capability and accurate controllability [8,9]. Therefore, it is necessary for the system operator to provide incentives to encourage these fast resources to participate in the regulation market.

Federal Energy Regulatory Commission (FERC) indicated in the Order 755 [10] that in order to encourage fast-ramping resources to provide regulation services, market design modifications should be implemented. Payments to the resources on regulation should include two components: a capacity payment representing the lost marginal cost of a resource, and a performance payment reflecting the actual regulation performance of the resource. To fulfil FERC Order 755, ISOs have made their market modifications. The concept of "Mileage", indicating the sum of absolute changes in generation outputs between different control intervals in a given period, has been widely accepted by ISOs to evaluate the performance of regulation resources [11].

In PJM Interconnection (PJM), the modified regulation market is implemented in the day-ahead market and is subject to real-time adjustment [12]. Resources willing to provide regulation services submit a regulation capacity offer price and a regulation mileage offer price. The market operator adjusts the offer of each resource based on its historical regulation performance. Then, the regulation offer price of the resource is calculated by summing up its adjusted regulation capacity offer price and its adjusted mileage offer price. In PJM, the operator clears the market by co-optimizing energy and regulation for each operating hour of the day subject to regulation capacity constraints. To emphasize regulation performance, the

* Corresponding author.
E-mail address: zwwang@eee.hku.hk (Z. Wang).

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highest adjusted mileage offer price among all selected resources determines the market mileage clearing price. The market capacity clearing price is calculated by the regulation offer price of the last selected resource minus the market mileage clearing price. After real-time operation, the market is settled based on the pre-determined capacity assigned to each resource, market clearing prices, and actual mileage obtained from each resource. Midcontinent ISO (MISO) implements a frequency regulation market similar to PJM except adjusting submitted offers for each resource individually [13,14]. MISO simplifies the process by using a system mileage multiplier, which is obtained based on the average historical performance of all resources. The regulation offer price of each resource is calculated by its capacity offer price plus the product of its mileage offer price and the system mileage multiplier. California ISO (CAISO) clears the regulation market subject to both regulation capacity constraints and regulation mileage constraints [15], which is different from PJM and MISO that are only with regulation capacity constraints. In this way, the mileage selected from a specific resource is affected by the selected capacity of the resource as well as its historical mileage. While CAISO has proposed to include both capacity and mileage constraints, a detailed formulation of the pricing mechanism has not been provided.

In real-time operation, regulation resources adjust their generation outputs in response to the system Automatic Generation Control (AGC) signals. With the implementation of a performance-based regulation payment, some system operators have modified or are modifying their AGC systems. For example, PJM has divided the regulation signals into traditional regulation signals (RegA), which are sent to conventional units, and fast response regulation signals (RegD), which are sent to fast-ramping resources [16]. In MISO, it is under discussion whether to set a separate regulation group for fast-ramping resources that are always deployed first or to modify the AGC distribution logic for these high-performance resources [17].

The performance-based frequency regulation payment has proven its effectiveness in U.S. power systems for its improving the system frequency quality and reducing the system regulation requirement [18]. In Europe, currently, there is no regulatory policy to include a regulation performance payment. Major European balancing markets compensate resources providing regulation with a payment for reserved capacity and a payment for real-time deployed energy [19]. However, the importance of fast-ramping storage units to provide regulation has already been acknowledged. For instance, in Germany, some pilot battery projects have been launched to manage frequency regulation and integrate renewable energy sources [20].

In addition to the practices of different system operators, some progress in recent academic papers also broadened the studies in this area. In [21], the planning issue of storage devices in a performance-based regulation market environment is addressed. In [22–24], optimal operation strategies are proposed for large-scale storage units and electric vehicles to maximize their profits in a performance-based regulation market. In these papers, regulation market clearing prices and AGC signals are assumed to be fixed. In [25–27], modified regulation market models are proposed to deal with the fluctuations caused by renewable energy sources by considering the system dynamics; however, the payment for regulation performance is not taken into account.

In this paper, to accurately present the relationship between regulation capacity and regulation mileage in the market clearing process, a performance-based regulation market model is first developed and their relationships are analysed based on the market simulation results. Furthermore, market-clearing prices for regulation capacity and regulation mileage are obtained and analysed. To reflect the clearing results from the proposed market model in real-time operation and to deploy regulation resources appropriately, an AGC allocation method is proposed. The proposed AGC allocation method uses a pro-rata approach and determines the

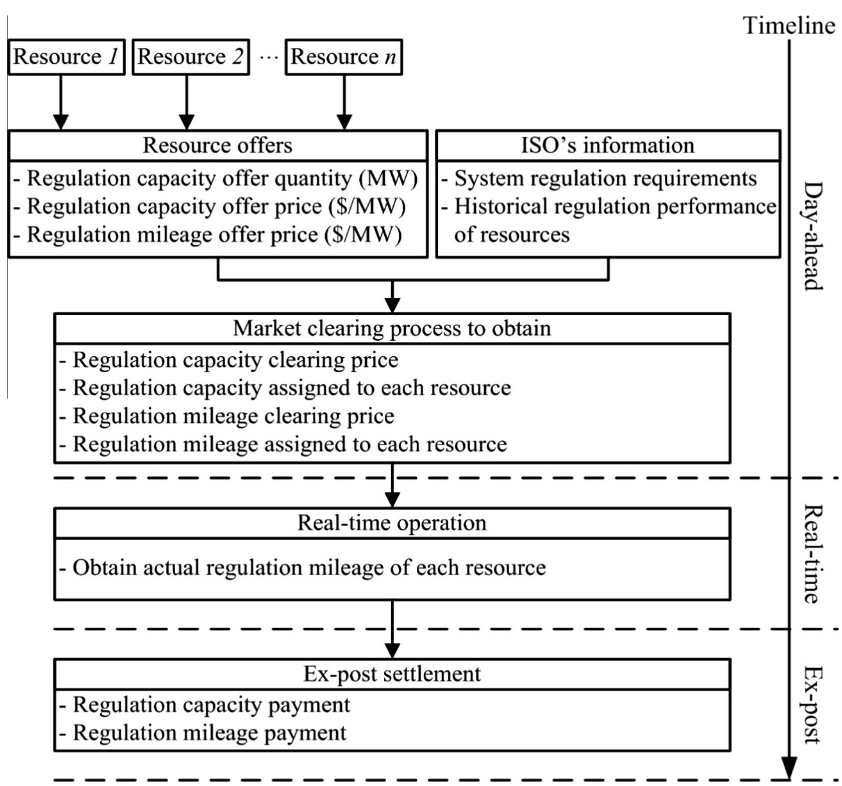

Fig. 1. Scheme of proposed performance-based frequency regulation market.

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participation factor of each regulation resource by taking into consideration the assigned regulation capacity and assigned regulation mileage of the resource. Thus, the final payment to each regulation resource depends on the pre-determined market clearing prices and the actual regulation performance of the resource in real-time operation.

The contribution of this paper could be justified by comparing with the existing industrial practices and recent academic papers. Firstly, in contrast to the recent papers focusing on developing operation strategies for fast-ramping storage units in a performance-based regulation market [22–24], in this paper, we focus on the regulation market design from the perspective of system operators who aim at giving efficient price signals to regulation providers and improving the frequency performance of the system. Secondly, although ISOs have already identified the importance of considering both regulation capacity and regulation mileage in their markets to represent regulation performance [12–17], the interactions between regulation capacity and regulation mileage are not straightforward. In practical applications, the simplified pricing mechanism indicates that the prices of regulation capacity and regulation mileage are loosely bundled. In this paper, we prove that the prices of regulation capacity and regulation mileage are strongly interacted and the relationship between the two market products is demonstrated by the decomposition of regulation market clearing prices. Finally, compared to existing literatures on performance-based regulation that generally address market design and AGC allocation separately [11,14,17], we go one step further by linking the market clearing results to the system AGC allocation algorithm.

The remaining parts of this paper are organized as follows: Section 2 gives the overall structure and timeline of the proposed frequency regulation market. Section 3 provides a detailed formulation of the proposed market model. The analysis of the characteristics and components of the clearing prices defined by Lagrange multipliers is conducted in Section 4. In Section 5, an AGC allocation method is proposed to accommodate the proposed market design. In Section 6, case studies are conducted and discussed. This paper is summarized and conclusions are drawn in Section 7.

2. Timeline of proposed performance-based regulation market

In this section, the basic structure of the proposed regulation market design is presented. The proposed frequency regulation market is integrated as part of the day-ahead market. Resources that are willing to provide regulation services should submit the following offers to the system operator on an hourly basis:

- Maximum regulation capacity (in MW) and capacity offer price (in \$/MW) of the resource.
- Regulation mileage offer price (in \$/MW) of the resource.
- Energy offers of the resource.

After collecting all the offers from market participants, the ISO clears the market using an optimization model to procure energy and ancillary services for each hour of the next operation day with the objective of minimizing the total procurement cost. The market is cleared based on resource offers, system regulation capacity requirement, regulation mileage requirement, and historical performance of regulation resources. The market is cleared to obtain the schedule of regulation resources, as well as the market clearing prices for regulation capacity and mileage.

In real-time operation, the regulation capacity and regulation mileage schedule obtained in the market clearing process will be used as input of the system AGC algorithm, so that the performance of regulation resources will be reflected by the AGC signal assignment.

The final payment to each regulation resource depends on market clearing prices obtained by the market model and its actual regulation performance. For each regulation resource, the payment consists of two parts: (1) a capacity payment which is the product of the capacity clearing price and assigned regulation capacity to the resource; (2) a performance payment which is the product of the mileage clearing price and the actual mileage of the resource. The schematic diagram of the proposed regulation market is illustrated in Fig. 1.

As introduced in Section 1, regulation services and energy are co-optimized in one market in U.S. electricity markets. In this paper, only the regulation market is studied. The co-optimization market will be studied in our later paper.

3. Performance-based regulation market formulation

The mathematical model of the performance-based regulation market lays the foundation of this paper. In this section, detailed formulation of the performance-based regulation market as an optimization problem is presented. We focus on regulation market, especially the relationship between regulation capacity and regulation mileage.

3.1. Notation

Indices	
T, t	Set and index of time periods
I_{RU}, I_{RD}	Set of regulation-up and regulation-down resources
i	Index of regulation resources
Constants	
$br_i^{t,UP}$	Regulation-up capacity offer price of resource i in time t
$br_i^{t,DN}$	Regulation-down capacity offer price of resource i in time t
$bm_i^{t,UP}$	Regulation-up mileage offer price of resource i in time t
$bm_i^{t,DN}$	Regulation-down mileage offer price of resource i in time t
$R_{sys}^{t,UP}$	System regulation-up capacity requirement in time t
$R_{sys}^{t,DN}$	System regulation-up capacity requirement in time t
$M_{sys}^{t,UP}$	System regulation-up mileage requirement in time t
$M_{sys}^{t,DN}$	System regulation-down mileage requirement in time t
$Mul_{sys}^{t,UP}$	System average regulation-up mileage multiplier in time t
$Mul_{sys}^{t,DN}$	System average regulation-down mileage multiplier in time t
$Mul_i^{t,UP}$	Average regulation-up mileage multiplier for resource i in time t
$Mul_i^{t,DN}$	Average regulation-down mileage multiplier for resource i in time t
$RUP_i^{t,max}$	Maximum biddable regulation-up capacity of resource i in time t
$RDN_i^{t,max}$	Maximum biddable regulation-down capacity of resource i in time t
Variables	
$R_i^{t,UP}$	Selected regulation-up capacity of resource i in time t
$R_i^{t,DN}$	Selected regulation-down capacity of resource i in time t

(continued on next page)

$M_i^{t,UP}$	Selected regulation-up mileage of resource i in time t
$M_i^{t,DN}$	Selected regulation-down mileage of resource i in time t

3.2. Objective

The objective of the performance-based regulation market is to minimize the total costs for procuring regulation-up and regulation-down services. No matter for regulation-up or regulation-down, the costs consist of two components: a regulation capacity cost and a regulation mileage cost. Both of them could be represented by linear functions expressed by the product of the procured quantity and the resource offer price. The objective function is shown as (1),

$$\min\left\{\sum_{t\in T}\left[\sum_{i\in I_{RU}}\left(br_i^{t,UP}\times R_i^{t,UP}+bm_i^{t,UP}\times M_i^{t,UP}\right)+\sum_{i\in I_{RD}}\left(br_i^{t,DN}\times R_i^{t,DN}+bm_i^{t,DN}\times M_i^{t,DN}\right)\right]\right\} \quad (1)$$

3.3. Constraints

System regulation capacity requirement constraints:

$$\sum_{i\in I_{RU}} R_i^{t,UP} \geqslant R_{sys}^{t,UP}, \quad \forall t \quad (2)$$

$$\sum_{i\in I_{RD}} R_i^{t,DN} \geqslant R_{sys}^{t,DN}, \quad \forall t \quad (3)$$

System regulation mileage requirement constraints:

$$\sum_{i\in I_{RU}} M_i^{t,UP} \geqslant M_{sys}^{t,UP}, \quad \forall t \quad (4)$$

$$\sum_{i\in I_{RD}} M_i^{t,DN} \geqslant M_{sys}^{t,DN}, \quad \forall t \quad (5)$$

Generally, the system mileage requirement is calculated by the system regulation capacity requirement multiplied by the system average mileage multipliers. The system average regulation mileage multiplier, $M_{sys}^{t,UP}$ (or $M_{sys}^{t,DN}$), represents the ratio between the total regulation-up (or regulation-down) mileage provided in real-time operation by all regulation resources and the total regulation-up (or regulation-down) capacity procured in the same operating hour over the previous week [28]. The system average mileage multipliers could be obtained from the historical regulation performance of the system.

Resource-specific regulation capacity upper and lower bounds:

$$0 \leqslant R_i^{t,UP} \leqslant RUP_i^{t,max}, \quad \forall i\in I_{RU}, t \quad (6)$$

$$0 \leqslant R_i^{t,DN} \leqslant RDN_i^{t,max}, \quad \forall i\in I_{RD}, t \quad (7)$$

Resource-specific regulation mileage upper and lower bounds:

$$R_i^{t,UP} \leqslant M_i^{t,UP} \leqslant Mul_i^{t,UP}\times R_i^{t,UP}, \quad \forall i\in I_{RU}, t \quad (8)$$

$$R_i^{t,DN} \leqslant M_i^{t,DN} \leqslant Mul_i^{t,DN}\times R_i^{t,DN}, \quad \forall i\in I_{RD}, t \quad (9)$$

The amount of regulation-up and regulation-down mileage cleared in the market are constrained by the cleared regulation capacity as well as average mileage multipliers of the resource. Here, the regulation mileage multiplier for each individual resource, $Mul_i^{t,UP}$ (or $Mul_i^{t,DN}$), is the ratio between the total regulation-up (or regulation-down) mileage provided in real-time operation by the resource and the total regulation-up (or regulation-down) capacity procured from the resource in the same operating hour over the previous week [28]. This constraint introduces a correlation between the selected regulation capacity and the selected regulation mileage of each resource.

4. Procurement of market clearing prices for regulation capacity and regulation mileage

The market clearing prices for regulation products in the proposed performance-based regulation market are defined in this section. A rigorous analysis of the characteristics and components of the clearing prices is also conducted to show the relationship between regulation capacity price and regulation mileage price.

4.1. Lagrange function

To demonstrate the pricing mechanism of the proposed market model, the Lagrange function of the optimization problem (1)–(9) is formulated as (10).

$$\begin{aligned}
L = {} & \Sigma_{t\in T}\left[\Sigma_{i\in I_{RU}}\left(br_i^{t,UP}\times R_i^{t,UP}+bm_i^{t,UP}\times M_i^{t,UP}\right)+\Sigma_{i\in I_{RD}}\left(br_i^{t,DN}\times R_i^{t,DN}+bm_i^{t,DN}\times M_i^{t,DN}\right)\right]\\
&+\Sigma_{t\in T}\left[\lambda^{t,RUP}\left(R_{sys}^{t,UP}-\Sigma_{i\in I_{RU}}R_i^{t,UP}\right)+\lambda^{t,RDN}\left(R_{sys}^{t,DN}-\Sigma_{i\in I_{RD}}R_i^{t,DN}\right)\right]\\
&+\Sigma_{t\in T}\left[\lambda^{t,MUP}\left(M_{sys}^{t,UP}-\Sigma_{i\in I_{RU}}M_i^{t,UP}\right)+\lambda^{t,MDN}\left(M_{sys}^{t,DN}-\Sigma_{i\in I_{RD}}M_i^{t,DN}\right)\right]\\
&+\Sigma_{t\in T}\left[\Sigma_{i\in I_{RU}}\alpha_i^{t,RUP}\left(R_i^{t,UP}-RUP_i^{t,max}\right)+\Sigma_{i\in I_{RU}}\beta_i^{t,RUP}\left(-R_i^{t,UP}\right)\right]\\
&+\Sigma_{t\in T}\left[\Sigma_{i\in I_{RD}}\alpha_i^{t,RDN}\left(R_i^{t,DN}-RDN_i^{t,max}\right)+\Sigma_{i\in I_{RD}}\beta_i^{t,RDN}\left(-R_i^{t,DN}\right)\right]\\
&+\Sigma_{t\in T}\left\{\Sigma_{i\in I_{RU}}\left[\alpha_i^{t,MUP}\left(M_i^{t,UP}-Mul_i^{t,UP}\times R_i^{t,UP}\right)+\beta_i^{t,MUP}\left(-M_i^{t,UP}+R_i^{t,UP}\right)\right]\right\}\\
&+\Sigma_{t\in T}\left\{\Sigma_{i\in I_{RD}}\left[\alpha_i^{t,MDN}\left(M_i^{t,DN}-Mul_i^{t,DN}\times R_i^{t,DN}\right)+\beta_i^{t,MDN}\left(-M_i^{t,DN}+R_i^{t,DN}\right)\right]\right\}
\end{aligned} \quad (10)$$

The Greek letters (λ, α, and β) in (10) represent non-negative dual variables of corresponding constraints. Regulation capacity and mileage clearing prices are determined based on these dual variables.

4.2. Definitions of market clearing prices

The regulation capacity clearing price is defined as the incremental cost/marginal cost caused by an additional unit of regulation capacity requirement. The regulation mileage clearing price is defined as the incremental cost/marginal cost caused by an additional unit of regulation mileage requirement.

Regulation-up capacity clearing price ($RCCP_{UP}^t$):

$$RCCP_{UP}^t = \partial L/\partial R_{sys}^{t,UP} = \lambda^{t,RUP}, \quad \forall t \quad (11)$$

Regulation-down capacity clearing price ($RCCP_{DN}^t$):

$$RCCP_{DN}^t = \partial L/\partial R_{sys}^{t,DN} = \lambda^{t,RDN}, \quad \forall t \quad (12)$$

Regulation-up mileage clearing price ($RMCP_{UP}^t$):

$$RMCP_{UP}^t = \partial L/\partial M_{sys}^{t,UP} = \lambda^{t,MUP}, \quad \forall t \quad (13)$$

Regulation-down mileage clearing price ($RMCP_{DN}^t$):

$$RMCP_{DN}^t = \partial L/\partial M_{sys}^{t,DN} = \lambda^{t,MDN}, \quad \forall t \quad (14)$$

4.3. Components of market clearing prices

To study the characteristics and components of market clearing prices, we take the regulation-up service as an example. Same conclusions hold for regulation-down services. According to the Karush-Kuhn-Tucker (KKT) conditions, at optimality, the following equations hold true:

$$\frac{\partial L}{\partial R_i^{t,UP}} = br_i^{t,UP} - \lambda^{t,RUP} + \alpha_i^{t,RUP} - \beta_i^{t,RUP} - \alpha_i^{t,MUP} \times Mul_i^{t,UP} + \beta_i^{t,MUP} = 0 \quad (15)$$

$$\frac{\partial L}{\partial M_i^{t,UP}} = bm_i^{t,UP} - \lambda^{t,MUP} + \alpha_i^{t,MUP} - \beta_i^{t,MUP} = 0 \quad (16)$$

From (15) and (16), we can derive the following expressions of regulation capacity clearing price and regulation mileage clearing price, as shown in (17) and (18):

$$\lambda^{t,RUP} = br_i^{t,UP} - \alpha_i^{t,MUP} \times Mul_i^{t,UP} + \beta_i^{t,MUP} + \alpha_i^{t,RUP} - \beta_i^{t,RUP} \quad (17)$$

$$\lambda^{t,MUP} = bm_i^{t,UP} + \alpha_i^{t,MUP} - \beta_i^{t,MUP} \quad (18)$$

And the slackness equations for (6) and (8) are expressed as shown in (19)–(22).

$$\alpha_i^{t,RUP}\left(R_i^{t,UP} - RUP_i^{t,max}\right) = 0 \quad (19)$$

$$\beta_i^{t,RUP}\left(-R_i^{t,UP}\right) = 0 \quad (20)$$

$$\alpha_i^{t,MUP}\left(M_i^{t,UP} - Mul_i^{t,UP} \times R_i^{t,UP}\right) = 0 \quad (21)$$

$$\beta_i^{t,MUP}\left(-M_i^{t,UP} + R_i^{t,UP}\right) = 0 \quad (22)$$

Based on (17)–(22), we use the following example to show the interaction of regulation capacity clearing price and regulation mileage clearing price.

Assuming resource *i* is the unit providing marginal regulation capacity, the assigned regulation capacity to resource *i* does not hit its upper or lower bound (i.e., $\alpha_i^{t,RUP} = \beta_i^{t,RUP} = 0$). In this situation, (17) becomes

$$\lambda^{t,RUP} = br_i^{t,UP} - \alpha_i^{t,MUP} \times Mul_i^{t,UP} + \beta_i^{t,MUP} \quad (23)$$

If this resource is also the unit providing marginal mileage (i.e., $\alpha_i^{t,MUP} = \beta_i^{t,MUP} = 0$), according to (18), the mileage clearing price is determined by the submitted offer price of the marginal unit, $\lambda^{t,MUP} = bm_i^{t,UP}$, and the regulation capacity price is determined by the capacity offer price of the same marginal unit, $\lambda^{t,RUP} = br_i^{t,UP}$. In this case, the system clearing prices are determined by the corresponding offer prices of the marginal unit.

However, if resource *i* is constrained by its minimum mileage requirement (i.e.,$\beta_i^{t,MUP} > 0, \alpha_i^{t,MUP} = 0$), by substituting (18) into (17), we have

$$\lambda^{t,RUP} = br_i^{t,UP} + \left(bm_i^{t,UP} - \lambda^{t,MUP}\right) \quad (24)$$

Therefore, under this assumption, the regulation capacity clearing price consists of two parts: (1) capacity offer price of the marginal unit, $br_i^{t,UP}$, and (2) mileage offer price of the resource minus mileage clearing price, $bm_i^{t,UP} - \lambda^{t,MUP}$. This is because that the selected regulation mileage of unit *i* hits its lower bound, then an extra 1 MW mileage needs to be procured if an additional megawatt of the capacity requirement is met by unit *i*. Therefore, the mileage offer price of unit *i*, $bm_i^{t,UP}$, should be included in the capacity clearing price. As the mileage payment of unit *i* is settled at $\lambda^{t,MUP}$, it should be excluded from the capacity payment to avoid repeated compensation. Thus, the second part of the regulation capacity clearing price is the difference between mileage offer price of the resource and the mileage clearing price.

In some extreme cases, if the system mileage requirement is very high, extra regulation capacity will be procured to satisfy the system mileage requirement. In this situation, the regulation capacity clearing price will be zero ($\lambda^{t,RUP} = 0$) and the mileage clearing price becomes

$$\lambda^{t,MUP} = bm_i^{t,UP} + \frac{br_i^{t,UP}}{Mul_i^{t,UP}} \quad (25)$$

In this case, the regulation capacity offer price of the resource is added to the mileage clearing price. The system mileage clearing price will be high and the total payment to regulation resources will be from the regulation mileage payment only.

4.4. Mileage requirement quantification

As pointed out in Section 4.3, if the system regulation mileage requirement is very high, the system operator will procure extra regulation capacity to fulfil the regulation mileage requirement. This will result in the regulation capacity cost being shifted to the regulation mileage clearing price, leading to a zero regulation capacity price and a high regulation mileage clearing price. This price distortion should be avoided as it will lead to a very high performance payment and the regulation resources will not receive any credit for reserving regulation capacity.

In order to mitigate the price distortion caused by mileage scarcity, the system operator should reformulate the mileage requirement before the market is cleared. Based on the submitted regulation capacity and mileage multipliers of each resource, the system operator ranks the resources in the descending order of mileage multipliers and calculates how much mileage can be obtained at most within the given regulation capacity requirement. Then, the system operator compares this maximum possible mileage with the pre-defined mileage requirement which is the product of the capacity requirement and the system mileage multiplier. The lower of the two will set the mileage requirement in the optimization problem formulation. It should be noticed that this mileage requirement adjustment could mitigate price distortion but cannot eliminate price distortion especially if there are market power holders exercising market power in the market.

4.5. Ex-post settlement

In the ex-post market settlement process, the payment to each regulation resource consists of two components: a capacity payment and a mileage payment. The capacity payment is determined by the capacity market clearing price and the assigned regulation capacity. This part of compensation is determined after the market is cleared and could be paid in advance as a premium.

$$Capacity\ Payment_i^{t,UP} = R_i^{t,UP} \times \lambda^{t,RUP} \quad (26)$$

The mileage payment is determined after real-time dispatch when the actual mileage, $M_{i,actual}^{t,UP}$, could be obtained.

$$Mileage\ Payment_i^{t,UP} = M_{i,actual}^{t,UP} \times \lambda^{t,MUP} \quad (27)$$

5. Implementing market clearing results in real-time AGC operation

In real-time operation, when a disturbance occurs, regulation resources modify their generation outputs in response to AGC signals to balance load deviations [29]. To reflect the clearing results

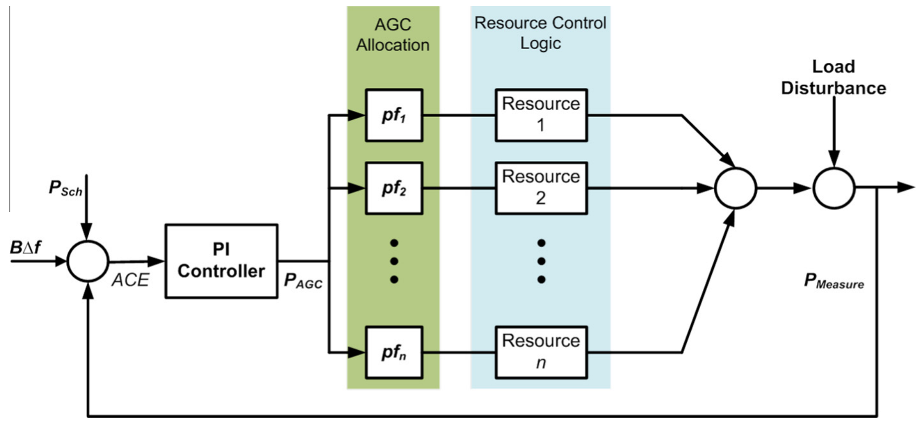

Fig. 2. General structure of AGC.

obtained in the market clearing process in real-time operation, a pro-rata AGC allocation method is proposed in this section.

Fig. 2 shows the general structure of the AGC system. The Area Control Error (ACE) is calculated by the measured power output ($P_{Measure}$) minus the scheduled interchange from tie-lines (P_{Sch}) plus the self-regulation frequency response ($B\Delta f$), where B is the frequency bias factor and Δf indicates the frequency deviation after disturbance. The output of the PI controller (P_{AGC}) is allocated for each regulation resource with a participation factor, pf_i. The participation factor of each resource determines how AGC signals are distributed. The qualities of AGC service are different based on which allocation method is used. Generally, the more AGC signals assigned to fast-ramping resources, the better the frequency quality will be. The allocation of AGC signals should be in consistent with the regulation market mechanism. For example, in locational marginal price (LMP)-based markets, the participation factor of each resource is inversely proportional to the marginal energy cost of the locating bus as regulation resources are financially compensated according to the deployed regulation reserve [30].

With the implementation of a performance-based regulation market, the AGC system should be updated accordingly to reflect the regulation performance in real-time operation. In the proposed performance-based regulation market, as the deployed regulation is compensated by the mileage provided in real-time operation. The regulation mileage of each resource should be taken into account when deciding the allocation approach of AGC signals. The adjustment of the allocation method should reflect the performance-based regulation market clearing results and should not be too complicated so that it could be easily implemented in the existing control system with minor modifications.

The proposed AGC allocation method is developed on a pro-rata basis as it has been pointed out in [31] that the pro-rata allocation method leads to a relatively faster activation of regulation and thus results in a better quality of frequency control than the merit-order method. The basic principle of the proposed AGC allocation method is to distribute the AGC signals in proportion with the assigned mileage of each resource. Furthermore, the allocated AGC signals should also be within the selected regulation capacity of the resource. If a resource is constrained by its selected regulation capacity, the outstanding AGC signals are re-allocated among other regulation resources that still have regulation capacity in proportion with the assigned mileage until the AGC signal is totally distributed. In each AGC controller step (generally several seconds), this allocation method could be mathematically expressed as an iterative process:

In the first stage, each resource is assigned a participation factor, $pf_i(1)$, that is in proportional with its assigned regulation mileage:

$$pf_i(1) = \begin{cases} \frac{M_i^{UP}}{\sum_{j \in I_{RU}} M_j^{UP}}, & P_{AGC} > 0 \\ \frac{M_i^{DN}}{\sum_{j \in I_{RD}} M_j^{DN}}, & P_{AGC} < 0 \end{cases} \tag{28}$$

In the kth stage, the participation factor of resource i, $pf_i(k)$, is expressed as follows:

If P_{AGC} is positive, indicating regulation-up service is activated,

$$pf_i(k) = \begin{cases} \frac{R_i^{UP}}{P_{AGC}}, & pf_i(k-1) \geqslant \frac{R_i^{UP}}{P_{AGC}} \\ pf_i(k-1) + \left(1 - \sum\limits_{j \in RU^{k-1}} \frac{R_j^{UP}}{P_{AGC}}\right) \times \frac{M_i^{UP}}{\sum\limits_{j \in (I_{RU} - RU^{k-1})} M_j^{UP}}, & pf_i(k-1) < \frac{R_i^{UP}}{P_{AGC}} \end{cases} \tag{29}$$

where RU^{k-1} represents the set of regulation-up resources that are allocated regulation signals larger than their selected regulation-up capacity in the $k-1$ stage (i.e., $j \in RU^{k-1} \iff pf_j(k-1) \geqslant (R_j^{UP}/P_{AGC})$).

If P_{AGC} is negative, indicating regulation-down service is activated,

$$pf_i(k) = \begin{cases} \frac{R_i^{DN}}{-P_{AGC}}, & pf_i(k-1) \geqslant \frac{R_i^{DN}}{-P_{AGC}} \\ pf_i(k-1) + \left(1 - \sum\limits_{j \in RD^{k-1}} \frac{R_j^{DN}}{-P_{AGC}}\right) \times \frac{M_i^{DN}}{\sum\limits_{j \in (I_{RD} - RD^{k-1})} M_j^{DN}}, & pf_i(k-1) < \frac{R_i^{DN}}{-P_{AGC}} \end{cases} \tag{30}$$

where RD^{k-1} represents the set of regulation-down resources that are allocated regulation signals larger than their regulation-down capacity in the $k-1$ stage (i.e., $j \in RD^{k-1} \iff pf_j(k-1) \geqslant (R_j^{DN}/-P_{AGC})$).

Eqs. (29) and (30) indicate that if the regulation signal allocated to resource i exceeds its assigned regulation capacity in the previous stage, the assigned regulation signal to this resource is capped at its assigned regulation capacity. It is also indicated that if resource i still has unallocated regulation capacity after the previous stage of allocation, the outstanding regulation signals will be further distributed to these resources with residual regulation capacity in proportion with their assigned regulation mileage. The iteration process converges (i.e., for each resource, $pf_i(k) = pf_i(k-1)$) when the regulation signal is totally distributed or the total regulation capacity is deployed. Then, the participation factor of each resource is obtained.

With the proposed AGC allocation approach, when the system regulation mileage requirement is high, a large amount of regulation mileage will be selected from fast-ramping resources. These

Table 1
Parameters and price offers of resources in base case.

Resource name	Maximum biddable capacity (MW)	Resource specific mileage multiplier	Capacity offer price ($/MW)	Mileage offer price ($/MW)
Gen1	35	4	10	2
Gen2	100	2	12	3
Gen3	50	1	20	1.5
ESS1	15	12	25	0

resources will have large participation factors and will respond more to regulation signals. When the system regulation mileage requirement is low, resources will be assigned a regulation mileage close to their selected regulation capacity. Thus, conventional thermal units with large regulation capacities will undertake more regulation responsibilities.

In summary, the proposed AGC allocation method links the market results with real-time operation. It activates more fast-ramping resources when high-performance regulation is needed and activates more conventional units when the regulation performance requirement is not high, facilitating the appropriate deployment of regulation resources.

6. Case studies and discussions

In this section, two test cases are studied. The first case is conducted on a simple system of four resources. A single time period is simulated to demonstrate the clearing procedure of the proposed market. The second case is based on IEEE 39-bus New England system and the 24-h time horizon is studied.

6.1. Base case example

In the base case, there are four resources participating in the market. Three of them are thermal generation units (Gen1, Gen2, and Gen3) and the rest is a flywheel energy storage system (ESS1). The market parameters are shown in Tables 1 and 2. Table 1 summarizes the parameters of regulation resources, and Table 2 presents the system regulation capacity and mileage requirement.

After the system operator collects all the offers and clears the market, the market clearing results are summarized in Table 3.

It is shown in Table 3 that Gen1, Gen2, and ESS1 are selected in the regulation market while Gen3 is excluded from the market. The clearing results show that the mileage clearing price, $2/MW, is equal to the offer price of Gen1, and the capacity clearing price, $13/MW, is different from the capacity offer price of any resource. This pricing mechanism could be illustrated in Fig. 3 intuitively.

After collecting the offers of each resource, the market operator forms the regulation capacity boundary and regulation mileage boundary as shown in Fig. 3. The capacity boundary is formed in the ascending order of $br_i^{t,UP} + bm_i^{t,UP}$, representing the marginal cost for procuring additional regulation capacity. The mileage boundary is formed in the ascending order of $bm_i^{t,UP} + br_i^{t,UP}/Mul_i^{t,UP}$, representing the marginal cost for procuring additional regulation mileage. The intersections of the system requirement with the two boundaries determine the system marginal units and market clearing prices.

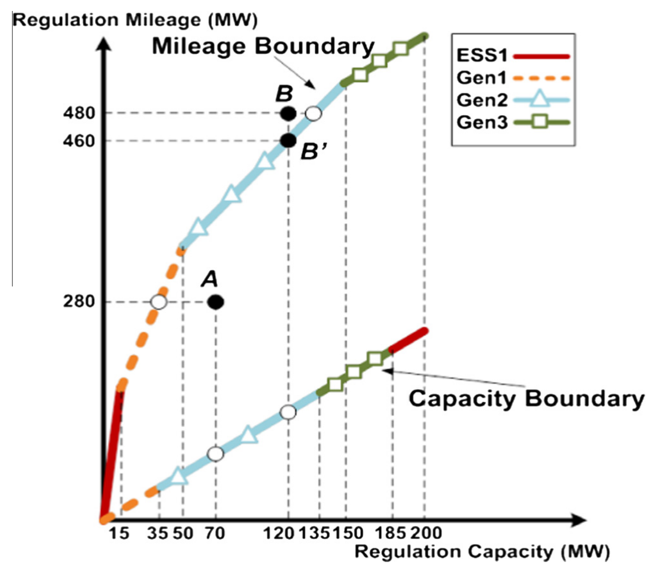

Fig. 3. Market clearing of the proposed regulation market design.

In the base case, the capacity boundary is in the sequence of Gen1, Gen2, Gen3, and ESS1 as their marginal regulation capacity cost are $12/MW, $15/MW, $21.5/MW, and $25/MW, respectively. The mileage boundary is formed in the sequence of ESS1, Gen1, Gen2, and Gen3 as their marginal regulation mileage cost are $2.08/MW, $4.5/MW, $9/MW, and $21.5/MW, respectively. The intersections of the system regulation requirement (A) with the boundary curves indicate that Gen2 is the capacity marginal unit and Gen1 is the mileage marginal unit. For Gen1, the total 35 MW regulation capacity is selected, and its assigned regulation mileage does not hit its upper or lower bound. Thus, Gen1 is the unit providing marginal regulation mileage, and its mileage offer price determines the system mileage clearing price. On the other hand, Gen2 is the resource providing marginal regulation capacity. However, as the selected regulation mileage of Gen2 hits its lower bound, an extra 1 MW mileage will be procured from Gen2 if an additional megawatt of the capacity requirement is met by Gen2. Therefore, the mileage offer price of Gen2 should be included in the capacity clearing price. As the mileage payment of Gen2 will

Table 2
System regulation requirement.

Capacity requirement (MW)	System mileage multiplier	System mileage requirement (MW)
70	4	280

Table 3
Market clearing results of proposed regulation market.

Resource name	Assigned capacity (MW)	Assigned mileage (MW)	Capacity clearing price ($/MW)	Mileage clearing price ($/MW)
Gen1	35	80	13	2
Gen2	20	20		
ESS1	15	180		

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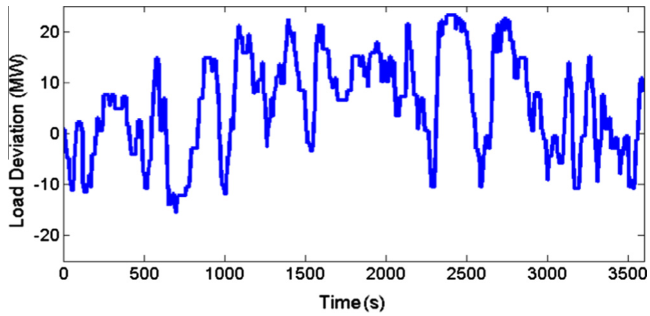

Fig. 4. System load deviations.

be settled at $2/MW, it should be excluded from the capacity clearing price to avoid repeated compensation. Thus, the total regulation capacity clearing price is expressed as the capacity offer price of the marginal resource ($12/MW) plus the mileage offer price of the capacity marginal resource ($3/MW) minus the regulation mileage clearing price ($2/MW), that is 12 + 3 − 2 = $13/MW.

In case the system regulation requirement falls outside the area between the capacity boundary and the mileage boundary, as indicated by point B, extra regulation capacity will be obtained to fulfil the system mileage requirement, resulting in a zero capacity clearing price and a high mileage clearing price. In order to mitigate this price distortion, the system requirement has to be pulled back to the mileage boundary, as indicated by point B′. After the system regulation requirement is adjusted from B to B′, the system mileage clearing price is reduced from $9/MW to $3/MW, and the capacity clearing price rises from $0/MW to $12/MW.

A traditional regulation market model neglecting regulation performance is simulated in comparison with the proposed regulation market model. In the traditional regulation market model, the market is cleared based on the merit order of capacity offer price of each resource. Based on the offer data provided in Table 1, both Gen1 and Gen2 will be selected a regulation capacity of 35 MW and the capacity clearing price will be settled at $12/MW.

To show the influence of the modification in regulation market design on the frequency performance of the system, system dynamic simulations are conducted under both market designs on MATLAB. The model used for simulation is developed based on the classic AGC model as depicted in Fig. 2, and the proposed AGC allocation method is applied. The system load deviations extracted from a real power system as shown in Fig. 4 are used as input information. Fig. 5 compares the generation outputs of regulation resources as well as the frequency performance of the system under the two market mechanisms.

The comparisons in Fig. 5 indicate that the implementation of a performance-based regulation market activates fast-ramping resources, which may be excluded in the traditional market, to provide regulation, and the modified AGC allocation method deploys these fast-ramping resources more often. With high-performance resources providing regulation services, the system frequency performance is much better than that of a traditional market without regulation performance considered.

Based on the simulation results, the ex-post payments of the proposed market design are obtained and summarized in Table 4. It is shown that for conventional thermal units, most of their regulation payments are from capacity payments as they provide a large portion of regulation capacity. For the high-performance resource, most of the regulation payment is from mileage payment because its fast ramping capability enables it to provide a large amount of regulation mileage in response to AGC signals.

6.2. IEEE 39-Bus case

In this case, the proposed performance-based regulation market model is simulated for a 24-h time horizon. The simulation is conducted on IEEE 39-bus New England system that contains 10 generating units [32]. The parameters of regulation resources are summarized in Table 5. Among all the ten generating units, ESS1 and ESS2 are energy storage devices that have large mileage multipliers, and the rest are thermal generating units. For simplicity, we make the assumption that each resource submits the same offer price for the 24 h.

The system regulation requirement is illustrated in Fig. 6. After the market is cleared, the scheduling of regulation resources is indicated as shown in Table 6, where “1” indicates the resource is selected to provide regulation in that hour and ‘–’ indicates the resource is excluded. The market clearing prices are shown in Fig. 7.

It is shown in Table 6 that when the system regulation capacity requirement is high (Hour 11–14), conventional thermal units with large regulation capacities but small mileage multipliers are major

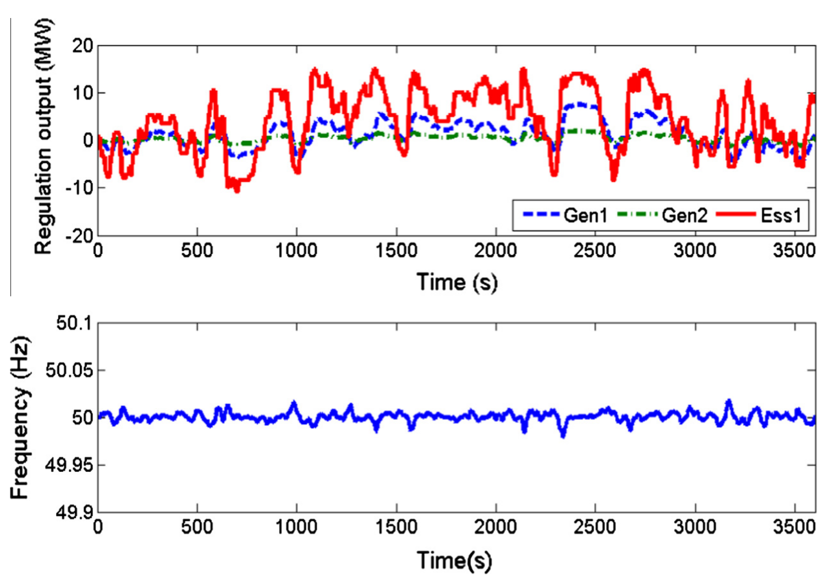

Fig. 5a. Regulation outputs of resources and system frequency response in proposed performance-based regulation market.

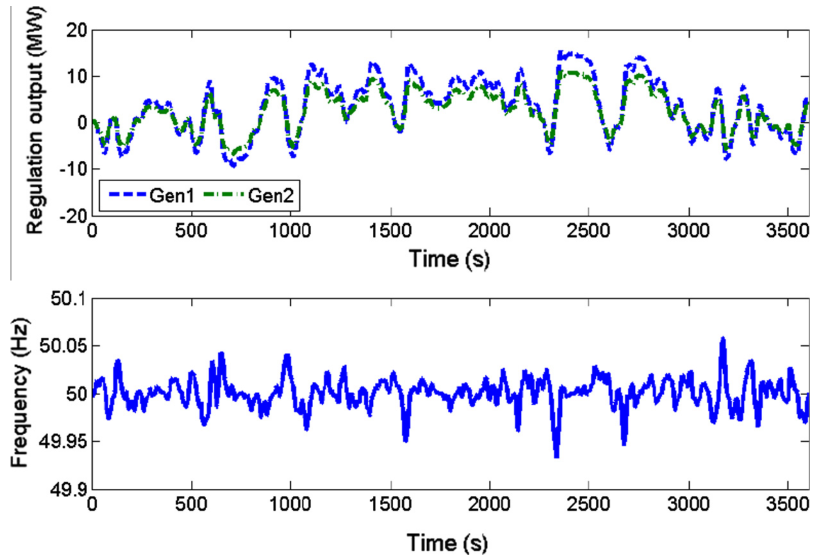

Fig. 5b. Regulation outputs of resources and system frequency response in traditional regulation market neglecting regulation performance.

Table 4
Ex-post payments of base case.

Resource name	Assigned capacity (MW)	Assigned mileage (MW)	Actual mileage (MW)	Capacity payment ($)	Mileage payment ($)	Total payment ($)
Gen1	35	80	99	455	198	653
Gen2	20	20	26	260	52	312
ESS1	15	180	218	195	436	631
Total	70	280	343	910	686	1596

Table 5
Parameters and price offers of resources in IEEE 39-Bus case.

Bus location	Resource ID	Maximum biddable capacity (MW)	Resource specific mileage multiplier	Capacity offer price ($/MW)	Mileage offer price ($/MW)
Bus 30	ESS 1	15	10	25	3.4
Bus 31	Gen 1	30	4	12	4
Bus 32	ESS 2	20	8	28	2.6
Bus 33	Gen 2	35	2.8	14	3
Bus 34	Gen 3	50	3.4	10	2.5
Bus 35	Gen 4	40	3.8	18	3
Bus 36	Gen 5	20	1.8	12	3.2
Bus 37	Gen 6	30	5	8	6
Bus 38	Gen 7	28	4	16	6
Bus 39	Gen 8	32	2	15	2.8

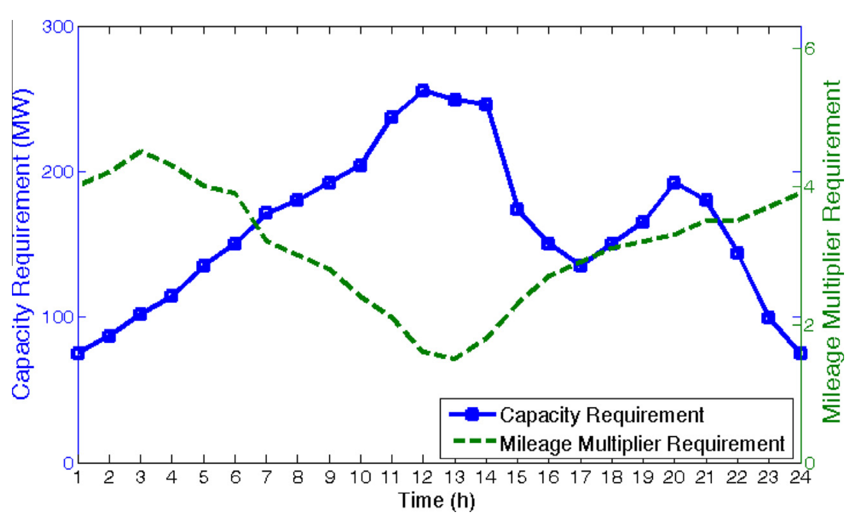

Fig. 6. Regulation capacity and mileage requirement of the system.

Table 6
Scheduling of regulation resources.

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
ESS 1	1	1	1	1	1	1	–	–	–	–	–	–	–	–	–	–	–	–	–	1	1	1	1	1
Gen 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
ESS 2	–	–	1	1	1	1	1	1	1	–	–	–	–	–	–	1	1	1	1	1	1	1	–	–
Gen 2	–	–	–	–	–	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	–	–
Gen 3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Gen 4	–	–	–	–	–	–	–	–	–	1	1	1	1	1	–	–	–	–	–	–	–	–	–	–
Gen 5	–	–	–	–	–	–	1	1	1	1	1	1	1	1	1	1	–	–	1	1	1	–	–	–
Gen 6	–	–	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	–
Gen 7	–	–	–	–	–	–	–	–	–	–	1	1	1	1	–	–	–	–	–	–	–	–	–	–
Gen 8	–	–	–	–	–	–	–	1	1	1	1	1	1	1	1	–	–	–	–	1	–	–	–	–

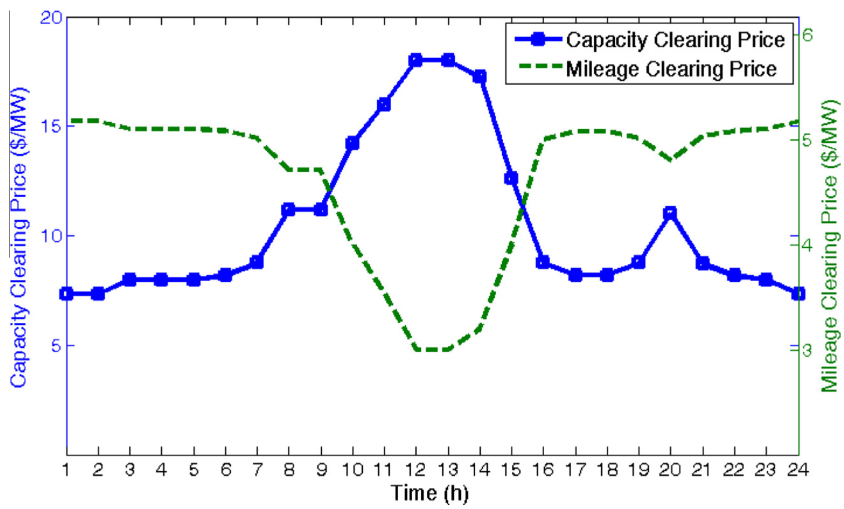

Fig. 7. Market clearing prices.

regulation providers. When the system regulation mileage requirement is high (Hour 1–6 and Hour 18–24), fast-ramping resources will participate in providing regulation. The market clearing prices shown in Fig. 7 also indicate that high regulation capacity requirement will lead to a high capacity clearing price, and high regulation mileage requirement will bring up the mileage clearing price. Thus, different types of regulation resources could be compensated fairly under the proposed market design.

System dynamic simulations are also conducted with real data for the total 24 h based on the market clearing results and the modified AGC allocation method. Fig. 8 illustrates the probability density function (PDF) of frequency deviations and the traditional regulation market neglecting regulation performance is also simulated for comparison. The visible differences between the two PDFs indicate that the implementation of a performance-based regulation will improve the frequency quality of the system.

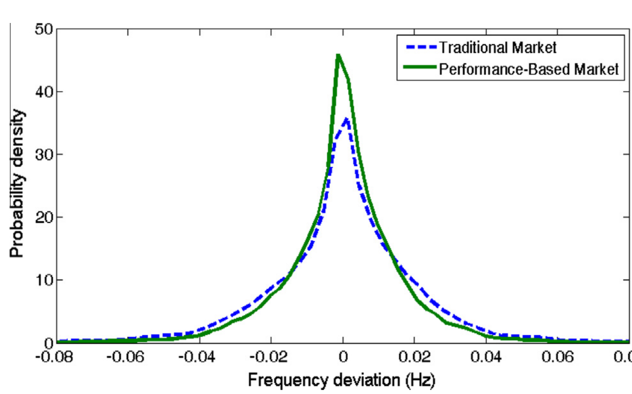

Fig. 8. PDFs of frequency deviations under proposed regulation market design and traditional regulation market neglecting regulation performance.

7. Conclusions

In this paper, a detailed formulation of a performance-based frequency regulation market model is presented. The components of the market clearing prices, and relationships between the capacity clearing price and mileage clearing price are analysed. An AGC allocation method is proposed to reflect the market clearing results in real-time operation. In case studies, the market clearing procedure is illustrated in an intuitive way. The results of the case studies show that with the implementation of a performance-based regulation market, different types of resources have different roles in providing frequency regulation. Under the proposed performance-based regulation market mechanism, fast-ramping energy storage units will have higher priority to be selected in the market. The market clearing prices for regulation products represent the system demand for regulation services. To mitigate price distortion caused by mileage scarcity, it is necessary to adjust the high regulation mileage requirement. By introducing the market clearing results in system AGC allocation algorithm, regulation resources selected in the market could be deployed appropriately in real-time operation, improving the frequency quality of the system. Furthermore, it is shown from the results of the case studies that when the regulation performance requirement is high, fast-ramping resources may contribute to a large portion of the total

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regulation provided even though they provide a small part of regulation capacity. In this case, fast-ramping resources will become price-makers and have market power, which gives us a direction for future work.

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