Effective flywheel energy storage (*FES*) offer strategies for frequency regulation service provision

Fang Zhang, Mirat Tokombayev, Yonghua Song and George Gross

Abstract*—The recent, deepening penetration of variable energy resources (*VERs*) subjects power systems to the highly variable, rapidly changing and uncertain generation outputs that the operators must manage effectively to provide reliable service. Such variability poses additional challenges to the management of the continual variability in system loads. Consequently, the frequency regulation service requirements are substantially increased over those for systems without these *VERs*. The attractive rapid response and fast ramping capability characteristics of flywheel energy storage (*FES*) technology can be exploited in the *FES* deployment for frequency regulation service provision. Such deployment requires the effective management of the limited *FES* capacity and storage capability. In this paper, we construct optimized frequency regulation service offer strategies for an *FES* unit into the day-ahead markets (*DAMs*) and their associated real-time markets (*RTMs*). An independent grid operator (*IGO*) procures the service competitively through such offers. The *FES* offer strategies are obtained from the deployment of a robust optimization approach, which explicitly considers the uncertain nature of automatic generation control (*AGC*) signals and the amount of *FES* stored energy. The optimization objective is to maximize the *FES* service provision into the *DAMs* and the *RTMs*. To meet this objective, the *FES* offers only into particular *DAMs* and provides additional frequency regulation service in the *RTMs* by taking advantage of the most recent information of *FES* stored energy, even in those hours in which the *FES* does not participate in the *DAMs*. A salient characteristic of the proposed offer strategies is that all offered services are guaranteed to be provided, regardless of the actual *AGC* signals. We illustrate the effectiveness of the proposed strategies with simulation studies that use PJM Interconnection historical *AGC* signal data. Representative results indicate that the proposed *FES* offer strategies result in guaranteed service provision without any exceptions. Such service provision represents a major improvement over that under the conventional strategy that offers the full *FES* capacity into each *DAM* but satisfies, on average, only 47.7 % of the regulation service requests. We also study the impacts of the Federal Energy Regulatory Commission (*FERC*) Order No. 764 that allows *DAM* periods shorter than one hour. Specifically, we quantify the significant benefits emanating from the flexibility for limited storage capability devices such as *FES* units in frequency regulation service provision via simulation studies.

***Index Terms*—Flywheel energy storage, ancillary service, day-ahead market, real-time market, frequency regulation, automatic generation control**

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F. Zhang and Y. Song are with the Department of Electrical Engineering, Tsinghua University, Beijing 100084, China (e-mails: zhangfang06@mails.tsinghua.edu.cn, yhsong@tsinghua.edu.cn). F. Zhang is currently a visiting Ph.D. student in the Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, 61801 IL, USA. M. Tokombayev and G. Gross are with the Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, 61801 IL, USA (e-mails: tokomba2@illinois.edu, gross@illinois.edu).

I. INTRODUCTION

A primary responsibility of a grid operator is to balance the generation and the load in the system in real time, as any imbalance between supply and demand results in a deviation of the system frequency from its nominal value [1]. Frequency regulation is an ancillary service which undertakes the short-term balancing operation and plays a vital role in the reliable operation of electric grids. A resource provides "regulation up (down)" service by increasing (decreasing) its power output. An independent grid operator (*IGO*) employs the automatic generation control (*AGC*) system to change the power outputs of such resources in order to keep the balance between the generation and the load in the area, and consequently maintains the system frequency and the tie-line power exchanges at their scheduled levels [2].

In a restructured environment, the frequency regulation service is procured on a competitive basis in markets. Many *IGOs* operate a single market to procure both regulation up and regulation down service while some other *IGOs* such as California Independent System Operator (*CAISO*) establish distinct markets for each product. Each frequency regulation service provider submits an offer, which consists of the quantity and the price of the service it is selling, into a market in which it wants to participate. After the market is closed, the responsible *IGO* clears the market by choosing a set of offers to meet the market demand, which is the requirement of frequency regulation service estimated by the *IGO*, and all cleared resources are paid at a uniform price.

The frequency regulation service is acquired through two markets with different time frames – the day-ahead markets (*DAMs*) organized for every period in a day with a typical duration of one hour, and the real-time markets (*RTMs*) set up for every subperiod in a period, usually five minutes in duration, to procure additional requirements of frequency regulation service arising in real time. All *DAMs* are cleared simultaneously during the day ahead, while each *RTM* is cleared in sequence at a time much closer to the subperiod it covers.

In recent years, the deepening penetration of variable energy resources (*VERs*), such as wind and solar photovoltaic, has significantly impacted the power system balancing operations. These resources come with limited controllability, and their outputs are subject to rapid and uncertain changes including possible intermittent behavior. Such volatility introduces additional variations to the continual variations in the loads in the system. [3]. Recent publications reported increasing requirements for frequency regulation as a result of deeper penetration of wind resources [4], [5], which imposes greater burdens on conventional balancing resources.

A particularly attractive resource is flywheel energy storage (*FES*) technology which has been deployed for frequency regulation service provision. *FES* units have rapid response, fast ramping capability, high efficiency and can undergo a considerably large number of charge/discharge cycles. Recent research indicates that such features render the *FES* to be particularly suitable to closely follow the continuously changing *AGC* signals [6]. As a specific example, the Beacon Power® Smart Energy® 25 flywheel, which has ratings of 100 *kW* × 15 *min* with a round-trip efficiency of 85 % and a design life of 20 years or 100,000 full depth of discharge cycles, can raise its output to full power capacity in under one second [7]. The positive experience with *FES* to date indicates that the *FES* units are effective in providing frequency regulation service and outperform conventional units [8].

More incentives are coming from the changes in policy emanating from recent Federal Energy Regulatory Commission (*FERC*) decisions. In October 2011, the *FERC* issued Order No. 755 which explicitly recognize the value of faster response time and higher ramping rates in the compensation of frequency regulation service providers [9]. This is evidently favorable to storage resources with outstanding performance such as *FES*. In June 2012, the *FERC* issued Order No. 764 that permits shorter duration for market periods below one hour to facilitate the integration of *VERs* and energy-limited resources into energy and ancillary service markets [10]. For storage-based frequency regulation service suppliers, this Order is beneficial since it provides more flexibility in the management of their limited storage capabilities. Such changes in policy add to further encouragement of the deployment of storage devices such as *FES* for the provision of frequency regulation service.

A salient characteristic of *FES* is its limited storage capability resulting in the inability to provide regulation up (down) service when its storage level is at the minimum (maximum). Therefore, it is difficult for an *FES* to offer guaranteed frequency regulation service around the clock as conventional generators do. In recognition of these limitations, certain *IGOs* including the New York Independent System Operator (*NYISO*) and the Independent System Operator of New England (*ISO-NE*), have introduced rules to allow energy limited resources to offer frequency regulation service regardless of their storage levels [11]. Absent such rules, an *FES* cannot simply offer its full capacity into each *DAM* since it may be unable to provide the offered service in operation, resulting in reduced service payments, penalties or even disqualification from the markets.

To become a reliable provider of frequency regulation service, an *FES* must explicitly take into account the uncertainty in *AGC* signals and the limitation on the storage capability in its offers. To address this problem, we propose offer strategies for an *FES* in this paper to maximize the frequency regulation service provision in the *DAMs* and offer additional service in the *RTMs* in light of the more up-to-date information of the storage level. The strategies are obtained via a robust optimization approach ensuring that the *FES* does not violates its storage capability limits in the extreme case that the *FES* is requested to provide the maximum quantity of a single type of service it offered into a market throughout the entire duration covered by the market. Consequently, the provision of frequency regulation service offered by the *FES* is guaranteed regardless of the actual *AGC* signals. We carry out simulations using historical *AGC* signal data from the PJM Interconnection (*PJM*) system to illustrate that 100 % of frequency regulation service requests are satisfied when the proposed strategies are adopted, while merely 47.7 % of service requests are met in average when the *FES* simply offers its full capacity of into each *DAM*.

The remaining part of this paper is organized as follows. The key assumptions and considerations to formulate the offer problem are addressed in Section II. We construct the offer strategies for *DAMs* and *RTMs* in Section III and IV, respectively. The proposed strategies are tested via simulations using *PJM* historical data in Section V, followed by a brief summary and a outlook of future work in Section VI.

II. Key Assumptions and Considerations

Given the small size of the *FES*, we assume the *FES* to be a price taker in the markets, and always submits offers with zero prices. We treat the general case of regulation up and regulation down service as distinct products with their individual market demands and resultant clearing prices. Therefore, the decision variables in the offer strategy are which markets to participate, and the amount of each service to offer in each market the *FES* participates.

In order to guarantee the provision of offered service, we formulate the problem as a constrained optimization program in which we explicitly represent the uncertainty in the varying *AGC* signals, by considering the limiting condition to occur in each service request, *i.e.*, in the case that regulation up (down) service is requested at the maximum amount offered over the entire duration of the market. If the storage capability limits of the *FES* are not violated in such extreme cases, the provision of the offered service can be guaranteed.

The *FES* is expected to participate in the *DAMs*, and may also offer additional service in the *RTMs*. The two markets operate on different time scales, and differ in the decision times and the proximity to the duration of the respective markets. Under these conditions, we decouple the offer strategy into the two markets into the solutions of two separate but related problems. Since the *DAM* results are determined in the day ahead and clearly impact the offers submitted into the *RTMs*, we first formulate offers into the *DAMs* for the maximum service provision. In the *RTMs*, the *FES* takes advantage of up-to-date information of the storage level to provide additional guaranteed service for increased revenues.

When making decisions for the *DAMs*, the *FES* may give up participating in the *DAMs* of some periods, and adjusts its storage level in these periods in case the *FES* becomes fully charged or discharged. Let e^m, e^M be the minimum and the

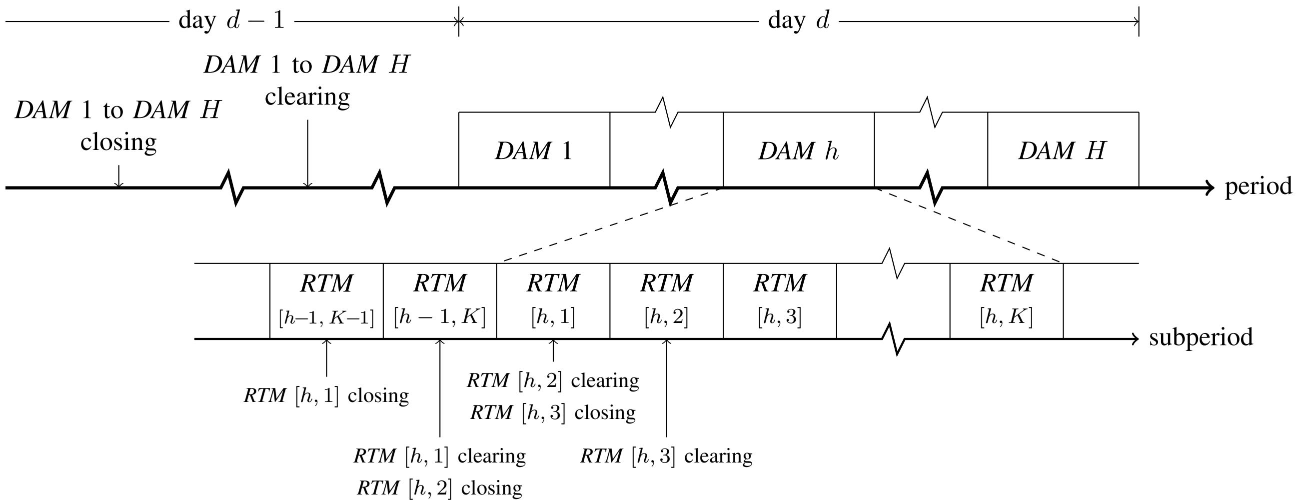

Fig. 1. Time lines of frequency regulation *DAMs* and *RTMs*

maximum storage level, and $p^{c,M}$, $p^{d,M}$ be the charge and the discharge capacity of the *FES*, respectively. Given the fairly small energy-to-power ratio of the *FES*, it is reasonable to assume that an *FES* is able to adjust its storage level from any point to the midpoint of its storage $e^0 = (e^m + e^M)/2$ over a single period during which it does not participate in the associated *DAM*, *i.e.*,

$$\frac{e^M - e^0}{p^{d,M}} = \frac{e^M - e^m}{2p^{d,M}} \leq \Delta$$

and

$$\frac{e^0 - e_m}{p^{c,M}} = \frac{e^M - e^m}{2p^{c,M}} \leq \Delta,$$

where Δ is the duration of one period.

To provide a concrete description for the *RTMs*, we assume that the *RTM* of a subperiod is closed one and a half subperiods ahead, and is cleared one subperiod later, *i.e.*, half a subperiod before the beginning of the subperiod of interest. We develop our approach to be sufficiently general to accommodate any other *RTM* closing and clearing time conventions. Let H be the number of periods in a day and K be the number of subperiods in each period. To make it short, we use the notation $[h, k]$ to represent the subperiod k of period h. Figure 1 illustrates the time lines of frequency regulation service markets.

We next formulate the offer strategy of the *FES* for each market using the concepts discussed in this section.

III. *DAM* Offer Strategy Formulation

We denote the set of all periods in a day as $\mathcal{H} = \{1, 2, \ldots, H\}$, and define $\mathcal{H}^p$ ($\mathcal{H}^n$) as the subset of $\mathcal{H}$ with (without) participation of the *FES* in the associated *DAMs*. It is clear that $\mathcal{H}^p \cup \mathcal{H}^n = \mathcal{H}$ and $\mathcal{H}^p \cap \mathcal{H}^n = \emptyset$. As discussed in Section II, the offer strategy involves the decision of the elements in $\mathcal{H}^p$ and the amount of regulation up (down) service $\hat{\kappa}_h^+$ ($\hat{\kappa}_h^-$) offered into each *DAM* of period $h \in \mathcal{H}^p$.

To maximize the provision of frequency regulation service in the H *DAMs*, we formulate the objective of the problem as

$$f = \sum_{h \in \mathcal{H}^p} \left(\hat{\kappa}_h^+ + \hat{\kappa}_h^- \right). \quad (1)$$

While we may assign a coefficient for each period to reflect the forecasted price or offerer-specified weight of the period, we adopt a uniform weight of 1. We made this choice in light of the uncertainty and the volatility of the *DAM* market results.

The amount of offered service cannot violate the physical charge $p^{c,M}$ and discharge $p^{d,M}$ capacities of the *FES*. Specifically, we require $\hat{\kappa}_h^+ \leq p^{d,M}$ and $\hat{\kappa}_h^- \leq p^{c,M}$ ($h \in \mathcal{H}^p$).

To ensure that the storage level in period $h \in \mathcal{H}^p$ does not violate the physical limits, we require the upper $\bar{e}_h$ and the lower $\underline{e}_h$ bounds of the storage level at the end of the period to satisfy

$$e^m \leq \underline{e}_h = \underline{e}_{h-1} - \hat{\kappa}_h^+ \Delta, \quad h \in \mathcal{H}^p \quad (2)$$

and

$$e^M \geq \bar{e}_h = \bar{e}_{h-1} + \hat{\kappa}_h^- \Delta, \quad h \in \mathcal{H}^p,$$

where Δ is the duration of each period. The lower (upper) bound of the storage level at the end of period $\underline{e}_h$ ($\bar{e}_h$) is obtained from the limiting case that the *FES* is requested to provide the maximum amount of regulation up (down) service it offered $\hat{\kappa}_h^+$ ($\hat{\kappa}_h^-$) throughout the entire period h.

Moreover, for a period $h \in \mathcal{H}^n$ with $h+1 \in \mathcal{H}^p$, the *FES* adjusts its storage level to e^0 so that

$$\underline{e}_h = \bar{e}_h = e^0, \quad h \in \mathcal{H}^n, h+1 \in \mathcal{H}^p. \quad (3)$$

The presence of disjunctive constraints results in a difficult-to-solve optimization problem. Nevertheless, considering the separable additive nature of the objective function (1), an optimal solution of the problem is readily available for the following analytical result.

Consider a subset of $\mathcal{H}$ consisting of a ($a \geq 1$) consecutive period(s) (starting from period l) in which the *FES* does not participates in the associated *DAM*(s), followed by b ($b \geq 1$) consecutive period(s) in which the *FES* does participate in the associated *DAM*(s). We define such a subset as a "segment":

$$\mathcal{H}^s = \{l, l+1, \ldots, l+a-1, l+a, \ldots, l+a+b-1\},$$

where $l, l+1, \ldots, l+a-1 \in \mathcal{H}^n$ and $l+a, l+a+1, \ldots, l+a+b-1 \in \mathcal{H}^p$.

Let $f^{s,+}$ ($f^{s,-}$) be the total amount of regulation up (down) service provided in the *DAMs* throughout the entire segment. In line with (2) and (3), we have

$$\underline{e}_{l+a-1} = e^0 - \sum_{h=l+a}^{l+a+b-1} \hat{\kappa}_h^+ \Delta \geq e^m.$$

Therefore,

$$f^{s,+} = \sum_{h \in \mathcal{H}^s} \hat{\kappa}_h^+ = \sum_{h=l+a}^{l+a+b-1} \hat{\kappa}_h^+ \leq \frac{e^0 - e^m}{\Delta} = \frac{e^M - e^m}{2\Delta}.$$

Note that the first a period(s) do not contribute to $f^{s,+}$ since the *FES* is not participating in the corresponding *DAM*(s). Analogously, we can prove that

$$f^{s,-} \leq \frac{e^M - e^m}{2\Delta}.$$

Hence, the total service provision throughout the entire segment satisfies

$$f^{s,+} + f^{s,-} \leq \frac{e^M - e^m}{\Delta}. \quad (4)$$

Equation (4) indicates that the maximum amount of frequency regulation service provision in the entire segment is a constant independent of a and b. Consequently, in order to maximize the objective function (1), we simply maximize the number of segments in $\mathcal{H}$, or equivalently, make each segment as short as possible. The shortest segment corresponds to $a = b = 1$, resulting in the solution

$$\mathcal{H}^{p,*} = \{2, 4, 6 \ldots, H\}$$

and

$$\mathcal{H}^{n,*} = \{1, 3, 5 \ldots, H-1\}.$$

It follows that the maximum quantities of the service that the *FES* can offer are

$$\hat{\kappa}_h^{+,*} = \hat{\kappa}_h^{-,*} = \frac{e^M - e^m}{2\Delta}, \quad h \in \mathcal{H}^{p,*},$$

and the maximum service provision throughout a day is

$$f^* = \sum_{h \in \mathcal{H}^{p,*}} \left(\hat{\kappa}_h^{+,*} + \hat{\kappa}_h^{-,*}\right) = \frac{H\left(e^M - e^m\right)}{\Delta}. \quad (5)$$

Using similar reasoning, by adding an assumption that the storage level at the beginning of the day settles at e^0, an equally good solution of $\mathcal{H}^{p,*'} = \{1, 3, 5, \ldots, H-1\}$ and $\mathcal{H}^{n,*'} = \{2, 4, 6, \ldots, H\}$ can be obtained with the same amount of service provision.

This result shows that in order to maximize the total amount of service provision in the *DAMs*, an *FES* should offer in the *DAM* of every alternative period and adjust its storage level to the midpoint in the other periods.

IV. *RTM* Offer Strategy Formulation

In the *RTMs*, we have up-to-date information of the storage level of the *FES*, which makes a major difference from the time at which we make decisions for *DAMs*. We take advantage of this fact to offer additional service in the *RTMs*.

Analogous to the offer strategy in the *DAMs*, the offer strategy of an *FES* in the *RTMs* involves the decision of whether to participate in the *RTM* of each subperiod $[h, k]$, and the amount of regulation up (down) service $\hat{\nu}_{h,k}^+$ ($\hat{\nu}_{h,k}^-$) to offer if the *FES* participates in the *RTM*. A notable difference between the two strategies is that the decisions for all *DAMs* are made together, while the decision for each *RTM* is made in sequence. On account of the time line of *RTMs* assumed in Section II, we make the decision for the *RTM* of subperiod $[h, k]$ two subperiods ahead, *i.e.*, at the end of subperiod $[h, k-3]$. This gives us enough time to make the decision since the *RTM* of interest is closing half a subperiod later.

Since the market results in the *DAMs* impact the *RTM* decisions, we need to formulate distinct offer strategies in the *RTMs* with *DAM* participation from those without *DAM* participation. We employ the outcomes of *DAMs* as the basis to determine the real-time offers into the *RTMs*.

We first address the offer strategy problem for the *RTM* of subperiod $[h, k]$ with *DAM* service awards ($h \in \mathcal{H}^p$). In such a subperiod, the *FES* must respect the results of the *DAM* of period h by ensuring that its storage level at the end of period h settles between $\bar{e}_h$ and $\underline{e}_h$ with the additional service offered in the associated *RTMs*. At the time of decision (the end of subperiod $[h, k-3]$), the *FES* has the following information:

- storage level $\varepsilon_{h,k-3}$ at the end of subperiod $[h, k-3]$
- *DAM* service awards κ_h^+ and κ_h^-
- *RTM* service awards $\nu_{h,k-2}^+$ and $\nu_{h,k-2}^-$ for subperiod $[h, k-2]$
- amounts of service $\hat{\nu}_{h,k-1}^+$ and $\hat{\nu}_{h,k-1}^-$ offered into the *RTM* of subperiod $[h, k-1]$

With these information, the *FES* can figure out the upper and the lower bounds of the storage level at the end of subperiod $[h, k-1]$:

$$\underline{\varepsilon}_{h,k-1} = \varepsilon_{h,k-3} - \left(\kappa_h^+ + \nu_{h,k-2}^+\right)\delta - \left(\kappa_h^+ + \hat{\nu}_{h,k-1}^+\right)\delta, \quad (6)$$

$$\bar{\varepsilon}_{h,k-1} = \varepsilon_{h,k-3} + \left(\kappa_h^- + \nu_{h,k-2}^-\right)\delta + \left(\kappa_h^- + \hat{\nu}_{h,k-1}^-\right)\delta, \quad (7)$$

where δ is the duration of each subperiod.

The lower (upper) bound of the storage level at the end of subperiod $[h, k]$ $\underline{\varepsilon}_{h,k}$ ($\bar{\varepsilon}_{h,k}$) is determined by the *DAM* results in period h, or more specifically, the lower (upper) bound of the storage level at the end of period h $\underline{e}_h$ ($\bar{e}_h$) and the regulation up (down) service award κ_h^+ (κ_h^-):

$$\underline{\varepsilon}_{h,k-1} = \underline{e}_h + \kappa_h^+(K-k)\delta,$$

$$\bar{\varepsilon}_{h,k-1} = \bar{e}_h - \kappa_h^-(K-k)\delta.$$

Figure 2 depicts the energy constraints for the offers in the *RTM*. The bounds of the storage level at the beginning and the end of subperiod $[h, k]$ are determined by the known information. Since the amounts of service offered into the *RTM* of the subperiod have to satisfy these energy constraints and be within the physical capacity limits, we obtain the maximum amounts of service that the *FES* may offer as

$$\hat{\nu}_{h,k}^+ = \min\left\{p^{d,M}, \frac{\underline{\varepsilon}_{h,k-1} - \underline{e}_{h,k}}{\delta}\right\} - \kappa_h^+,$$

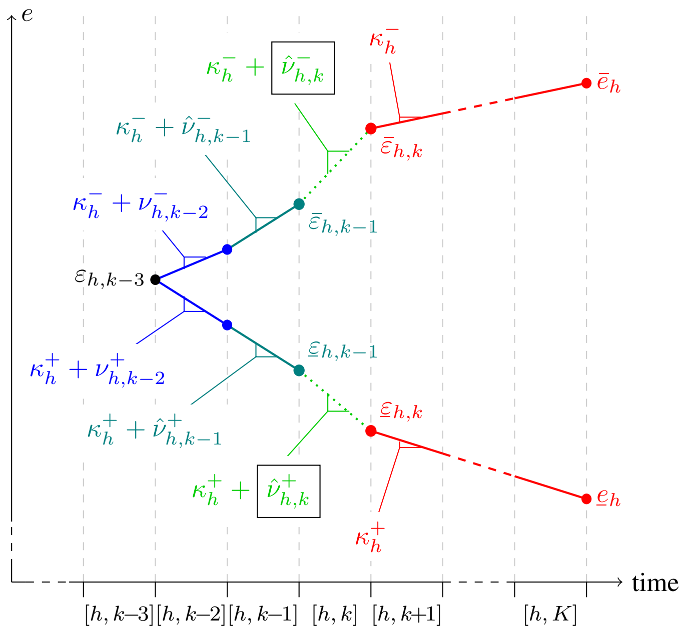

Fig. 2. Energy constraints for the offers in the *RTM* of subperiod k in period h with *DAM* participation

$$\hat{\nu}^-_{h,k} = \min\left\{p^{c,M}, \frac{\bar{e}_{h,k} - \bar{\varepsilon}_{h,k-1}}{\delta}\right\} - \kappa_h^-.$$

Note that *IGOs* usually impose a minimum amount of service ν^m for any valid offer. In this case, if either $\hat{\nu}^+_{h,k}$ or $\hat{\nu}^-_{h,k}$ is smaller than ν^m, the *FES* has to give up participating in the *RTM* of subperiod $[h,k]$.

With respect to the *RTM* of subperiod $[h,k]$ without the participation in the *DAM* ($h \in \mathcal{H}^p$), the formulation of the offer strategy is similar but with no *DAM* service awards (κ_h^+ and κ_h^-); the bounds of the storage level at the end of subperiod $[h,k]$ are only limited by the storage capability of the *FES* (e^m and e^M). Figure 3 exhibits the energy constraints for the offers in such *RTMs*. Moreover, the *FES* does not participate in the *RTMs* of the last one or more subperiods in period h in which it adjusts the storage level to e^0 in order to provide service offered in the *DAM* of the next period. For example, if $\Delta = 1$ *h* and $\delta = 5$ *min* ($K = 12$), an *FES* with an energy-to-power ratio of 15 *min* needs at most two subperiods to adjust its storage level from any point to e^0; consequently, the *FES* participates only in the *RTMs* of the first 10 subperiods.

Analogous to (6) and (7), we obtain that

$$\underline{\varepsilon}_{h,k-1} = \varepsilon_{h,k-3} - \nu^+_{h,k-2}\delta - \hat{\nu}^+_{h,k-1}\delta,$$

$$\bar{\varepsilon}_{h,k-1} = \varepsilon_{h,k-3} + \nu^-_{h,k-2}\delta + \hat{\nu}^-_{h,k-1}\delta.$$

And the maximum amounts of service that the *FES* may offer in the *RTM* are

$$\hat{\nu}^+_{h,k} = \min\left\{p^{d,M}, \frac{\underline{\varepsilon}_{h,k-1} - \underline{e}_{h,k}}{\delta}\right\},$$

$$\hat{\nu}^-_{h,k} = \min\left\{p^{c,M}, \frac{\bar{e}_{h,k} - \bar{\varepsilon}_{h,k-1}}{\delta}\right\}.$$

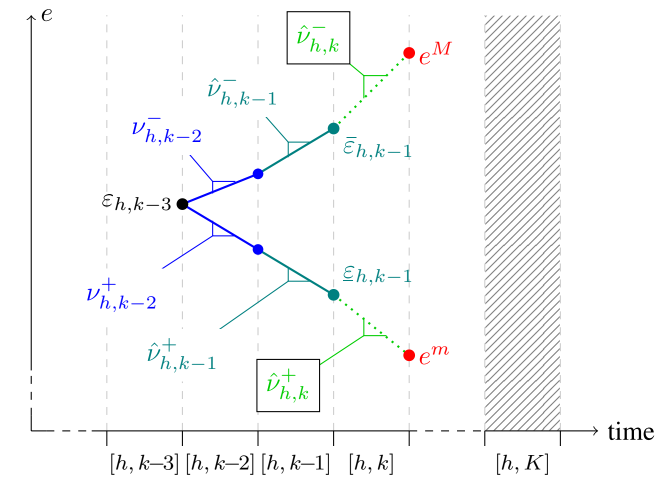

Fig. 3. Energy constraints for the offers in the *RTM* of subperiod k in period h without *DAM* participation

V. Simulation Studies

In this section, we present representative simulation results using the proposed strategies. The 2-second *AGC* signal data in a period of 32 consecutive days from 12/18/2012 to 1/18/2013 are obtained from the *PJM* system[1]. The normalized signals are scaled in line with the offered quantities of frequency regulation service by the *FES* in the *DAMs* and the *RTMs*. The parameters used in the simulations are listed in Table I.

TABLE I
PARAMETERS USED IN SIMULATIONS

Parameter	Value
Δ	1 *h*
δ	5 *min*
ν^M	1 *MW*
$p^{d,M}$, $p^{c,M}$	20 *MW*
e^m	1 *MWh*
e^M	6 *MWh*

The daily service provision in the study period are presented in Figure 4. The results indicate that the total provision of frequency regulation service in the *DAMs* remains constant among different days in line with the formulation presented in Section III. On the other hand, the provision in the *RTMs* changes from day to day but the differences are small.

We note that any service offered by the proposed strategies is guaranteed; no matter what the actual *AGC* signals turn out to be, the *FES* is always able to follow the signals. However, we observe that the proposed offer strategy in the *DAMs* is quite conservative; the *FES* guarantees its service at the cost of less utilization of its capacity due to the limited storage capability. As a comparison, we simulate a straightforward strategy that simply offers the maximum capacity into all

[1] *PJM* has two types of *AGC* signals: *RegA* and *RegD*. Both are based on the area control error (*ACE*), which measures the weighted sum of the power and frequency imbalances in the area, but *RegD* signals are from a high-pass filter and consist of more high-frequency components than *RegA* signals. Since most *IGOs* produce only one type of *AGC* signal from low-pass filters such as *RegA* signals, *RegA* signal data are used in this paper.

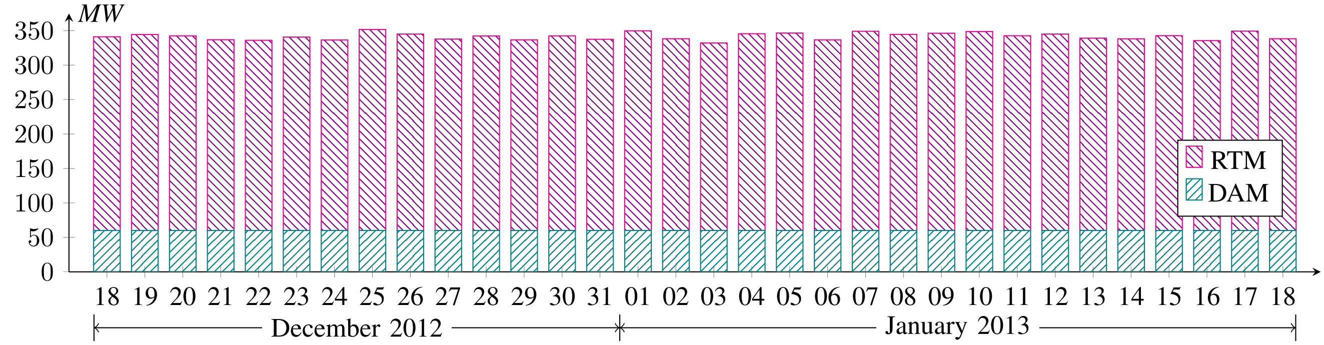

Fig. 4. Daily service provision with the proposed strategies under the *PJM* historical signal data

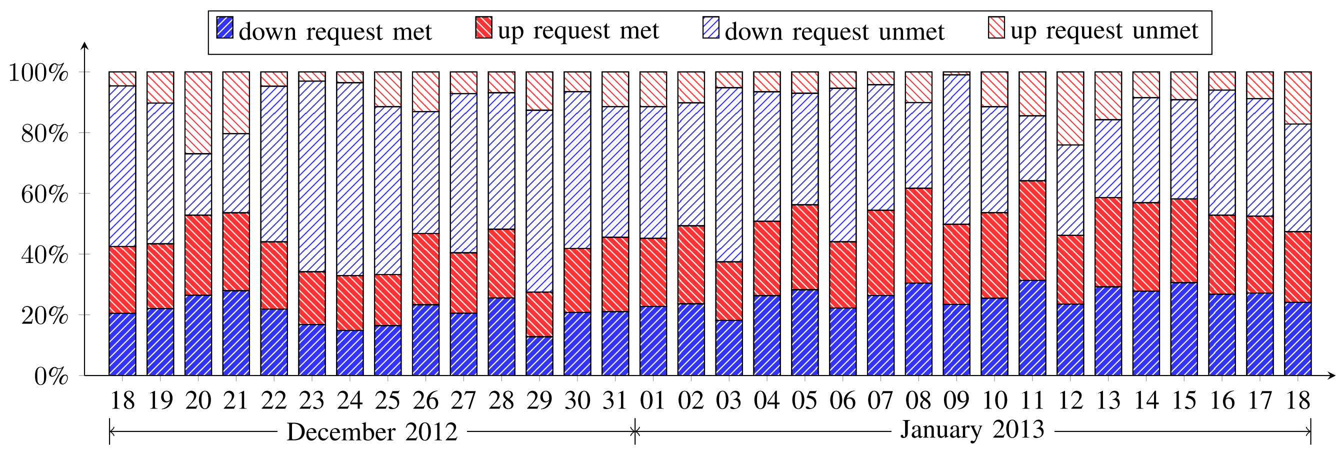

Fig. 5. Percentages of met and unmet service requests for the full-capacity offer strategy

the *DAMs*. In this case, the offered service is no longer guaranteed; the *FES* fails to meet a regulation up (down) request when its storage level is at the minimum (maximum). The percentages of met and unmet service requests throughout a day are exhibited in Figure 5, indicating that only 47.7% of the requests are satisfied in average. Although higher service provision can be achieved at 20 *MW/h* × 24 *h* × 2 = 960 *MW* per day in this case, the poor service quality may result in penalty or even disqualification from the markets.

The regulation service provision throughout a single day (12/23/2012) is shown in Figure 6. Taking advantage of the up-to-date information in the real-time operation, the *FES* is able to offer additional service in the *RTMs* while the provision of the offered service in the *DAMs* is guaranteed. When the *FES* provides more regulation up service (discharges) more in the real time, it will offer more regulation down service in subsequent *RTMs*, and vice versa.

A. Impact of DAM Period Durations

The *FERC* Order No. 764 permits *DAM* periods shorter than one hour which provides more flexibility to energy limited resources. We demonstrate the impact of shorter periods on the provision of frequency regulation service by the *FES* in a quantitative manner by carrying out simulations of cases with different Δ. The results are presented in Table II. The service provision when $\Delta = 15$ *min* in the same day as Figure 6 (12/23/2012) is shown in Figure 7. The duration of each *RTM* remains to be 5 *min*.

TABLE II
AVERAGE DAILY SERVICE PROVISION BY *FES* W.R.T. Δ

Δ *(min)*	*DAM (MW)*	*RTM (MW)*	Total *(MW)*
60	60.0	281.9	341.9
30	120.0	219.1	339.1
20	180.0	147.5	327.5
15	240.0	87.5	327.5

The results show that the *DAM* service provision is in reverse proportion to Δ, which is consistent with Equation (5). Smaller Δ imposes less restrictions for the *FES* to offer in the *DAMs*. Although the total service provision becomes slightly smaller, it is still favorable to the *FES* as it can offer more service in the *DAMs* than in the *RTMs* where the market demands are more uncertain.

VI. CONCLUDING REMARKS

In this work, we propose the offer strategies for the maximum provision of frequency regulation service by an *FES* into the *DAMs* and the *RTMs*. This research reveals that the optimal strategy of an *FES* in the *DAMs* is to offer the largest amount of service allowed by its storage capability in one period, and not participating in the following period to adjust its storage level back to the midpoint. In the *RTMs*, it is possible for the *FES* to take advantage of the more up-to-date information of its storage level to offer additional frequency regulation

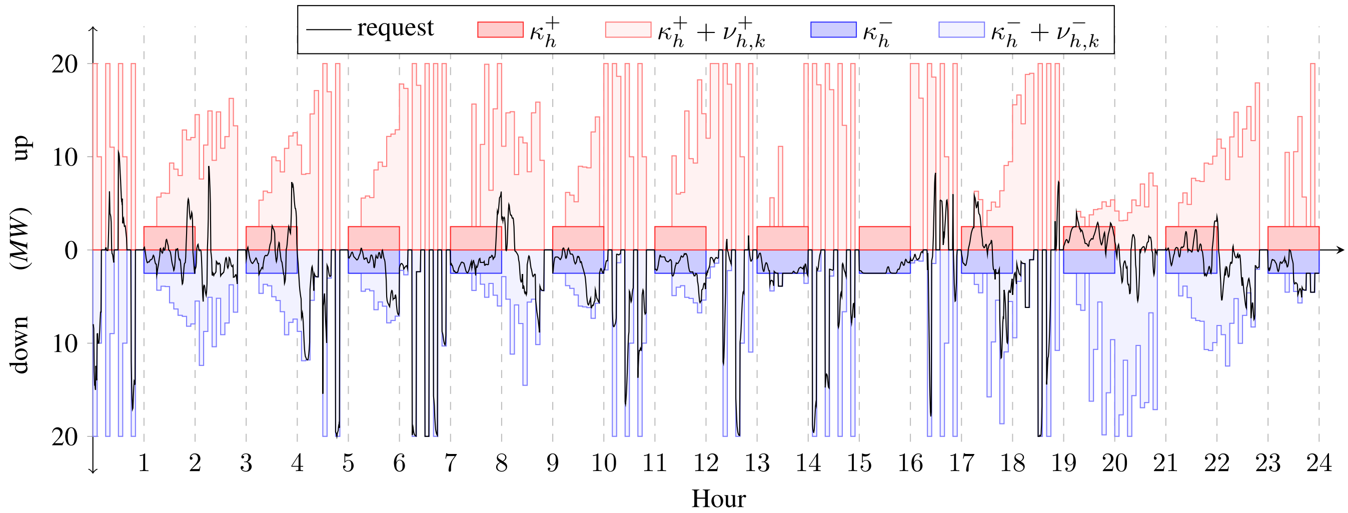

Fig. 6. Service provision with the proposed strategies under the *PJM* historical signal data on 12/23/2012 ($\Delta = 1$ h)

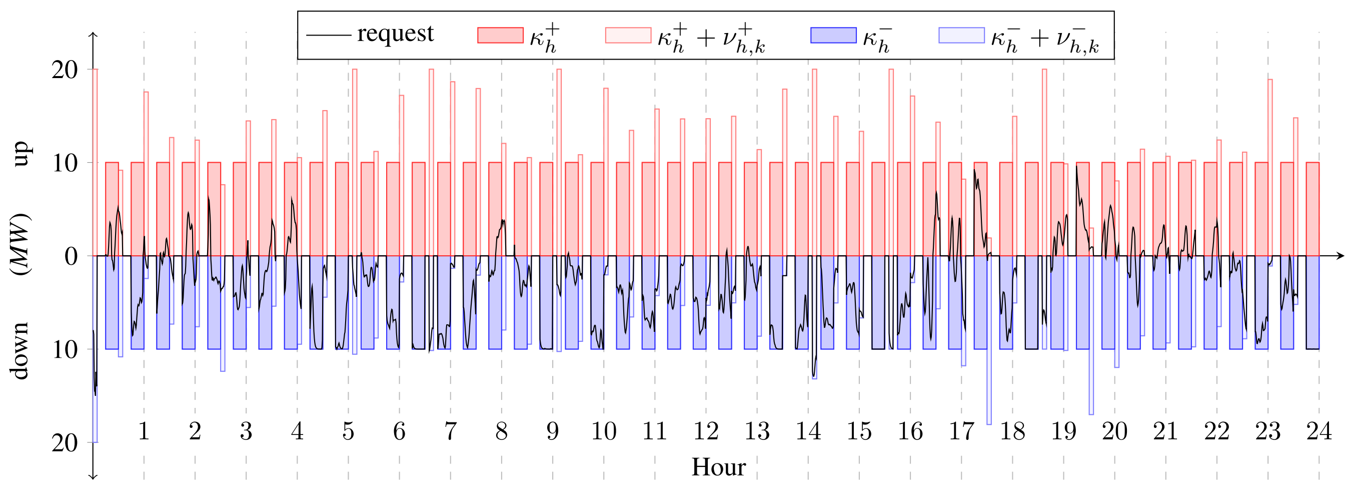

Fig. 7. Service provision with the proposed strategies under the *PJM* historical signal data on 12/23/2012 ($\Delta = 15$ min)

service. Further study indicates that shortening *DAM* periods as permitted under the *FERC* Order No. 764 is conducive to more service provision in the *DAMs*.

We note that the robust optimization results in this paper constitute rather conservative offer strategies as they are the solutions of limiting cases to provide the same service for each regulation signal throughout the optimization period. In actual operations such situations are quite unlikely due to the rapidly changing conditions on a grid. We are developing more risk-bearing strategies that we shall report on in our future papers.

REFERENCES

[1] M. Tokombayev, "Effective utilization of flywheel energy storage (FES) for frequency regulation service provision," M. Sc. thesis, University of Illinois at Urbana-Champaign, 2014.

[2] B. J. Kirby, "Frequency regulation basics and trends," Oak Ridge National Laboratory, Tech. Rep., Dec. 2004.

[3] H. Bevrani, A. Ghosh, and G. Ledwich, "Renewable energy sources and frequency regulation: survey and new perspectives," *IET Renewable Power Generation*, vol. 4, no. 5, p. 438, 2010.

[4] Y. Makarov, C. Loutan, J. Ma, and P. de Mello, "Operational impacts of wind generation on california power systems," *IEEE Transactions on Power Systems*, vol. 24, no. 2, pp. 1039–1050, 2009.

[5] R. Walling, L. Freeman, and W. Lasher, "Regulation requirements with high wind generation penetration in the ERCOT market," in *Proceedings of the 2009 IEEE/PES Power Systems Conference and Exposition (PSCE '09)*, Seattle, WA, USA, Mar. 15–18, 2009.

[6] N. Lu, M. R. Weimar, Y. V. Makarov, F. J. Rudolph, S. N. Murthy, J. Arseneaux, and C. Loutan, "Evaluation of the flywheel potential for providing regulation service in California," in *Proceedings of the 2010 IEEE PES General Meeting*, Minneapolis, MN, USA, Jul. 25–29, 2010.

[7] Beacon Power, LLC. (2013, Apr.) Flywheel energy storage system technical data sheet. Tyngsboro, MA, USA. [Online]. Available: http://www.beaconpower.com/files/FESS_Tech_Data_Sheet.pdf

[8] J. Eyer, "Benefits from Flywheel Energy Storage for Area Regulation in California – Demonstration Results," Sandia National Laboratories, Tech. Rep., Oct. 2009.

[9] "Order No. 755: Frequency Regulation Compensation in the Organized Wholesale Power Markets," Federal Energy Regulatory Commission, USA, Oct. 2011. [Online]. Available: http://www.ferc.gov/whats-new/comm-meet/2011/102011/E-28.pdf

[10] "Order No. 764: Integration of Variable Energy Resources," Federal Energy Regulatory Commission, USA, Jun. 2012. [Online]. Available: http://www.ferc.gov/whats-new/comm-meet/2012/062112/E-3.pdf

[11] M. L. Lazarewicz and T. M. Ryan, "Integration of flywheel-based energy storage for frequency regulation in deregulated markets," in *Proceedings of the 2010 IEEE PES General Meeting*, Minneapolis, MN, USA, Jul. 25–29, 2010.