# EFFECTIVE UTILIZATION OF FLYWHEEL ENERGY STORAGE (*FES*) FOR FREQUENCY REGULATION SERVICE PROVISION

BY

MIRAT TOKOMBAYEV

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Electrical and Computer Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2014

Urbana, Illinois

Adviser:

Professor George Gross

# ABSTRACT

The deeper penetration of variable energy resources (*VER*s) in the form of wind farms and solar photovoltaic systems has impacted power system operations and planning in many ways. Today, renewable energy resources constitute a significant portion of new power generation capacity additions. As the outputs of renewable generation resources are function of the climatic conditions at their geographic locations – and over which the resource operators have no control – and the current renewable technologies provide only limited controllability, the renewable outputs are subject to, by and large, uncontrollable, rapid and uncertain changes. Such volatility in the renewable outputs, that may also include intermittent behavior, can affect power systems operations significantly. Indeed, the continual variability impacts introduce new complications due to their interactions with the impacts of the continuously changing loads in the system. In particular, such interactions may exacerbate the challenge to provide the critical function to maintain the supply-demand balance around the clock. Given the limited controllability over the renewable resources, system operators have no choice but to impose additional burdens on the controllable conventional generation resources. Many of these resources, however, have rather slow response times and limited ramping capabilities resulting in less than ideal performance in the provision of the second-by-second supply-demand balance – the so-called frequency regulation service. This service, also known by the technical term of automatic generation control (*AGC*), is absolutely essential to maintain the frequency of the power system at its nominal value, which is 60 Hz in the United States and 50 or 60 Hz in other countries.

The recent advancements on the storage technology front indicate great potential in terms of applications to power systems for frequency regulation service. A particularly exciting development is the integration into the power system of storage devices known as flywheel

energy storage (*FES*). In this thesis, we investigate the effective utilization of *FES* for frequency regulation service provision via the competitive markets for such service.

The *FES* utilization in frequency regulation service provision presents a number of challenges. A *FES* unit has a relatively low energy-to-power ratio, a situation that implies a clear limitation to its ability to provide frequency regulation over longer periods of time in only a single direction. Such a limitation, consequently, constrains the amount of service the *FES* unit can offer. As the frequency regulation service is procured in the competitive environment through market mechanisms, the *FES* physical limitations and the uncertainty associated with the second-by-second requirements of the system make the formulation of appropriate offer strategies for a *FES* unit a challenging task. To address all these challenges, we have developed a comprehensive approach to effectively utilize the *FES* to provide guaranteed frequency regulation service to the grid. We prepared this thesis to discuss the development of the approach and describe its application to various studies. We demonstrate the capability of the developed approach and quantify the improved performance over existing techniques through various case studies using actual 2011 *AGC* signal and price data from two large systems – the *CAISO* and the *PJM*. The representative results clearly indicate that the proposed approach generates offer strategies that result in better utilization of *FES* to provide guaranteed frequency regulation service.

*To my family*

# ACKNOWLEDGMENTS

I would like to thank my adviser, Professor George Gross, for the guidance and support he gave me throughout my studies at the University of Illinois at Urbana-Champaign. His willingness to provide help and a critical eye have taught me to strive for continuous improvements.

I also thank my colleagues and friends: Kai, Yannick, Isaac, Ti, Ada, and Marco with whom I spent a lot of time during the past two years and whose lively discussions have made a valuable contribution into my research. I would also like to thank all the students, faculty and staff in the Power and Energy Group for their constant support and encouragement.

Finally, nothing would have been possible without the love of my family, who has always supported me during my stay in the United States.

# TABLE OF CONTENTS

# CHAPTER 1

# INTRODUCTION

This thesis deals with the utilization of flywheel energy storage for frequency regulation service provision. In this chapter, we start by discussing the motivation and background of our research to set the stage for the work presented in the thesis. We provide a brief summary of the frequency regulation service provision by storage technology and review the prior work in this area. Then, we present the scope and the contribution of the work. We end by outlining the contents of the chapters that follow.

## 1.1 Motivation and Background

The deeper penetration of variable energy resources (*VER*s), such as wind and solar photovoltaic, has significantly impacted power systems operations and planning. Today the renewable resources already constitute a significant portion of new power generation capacity additions. As the outputs of renewable generation resources are determined by climatic conditions at their locations and over which the resource operators have no control, and the current renewable technologies provide only limited controllability, the renewable outputs are

subject to rapid and uncertain changes. Such volatility in the renewable outputs, that may also include intermittent behavior, can affect power systems operations significantly and introduce additional complications to the impacts of the continuously changing loads in the system. In order to maintain the supply-demand balance around the clock, system operators must impose additional burdens on the controllable generation resources. Many of these resources, however, have rather slow response times and limited ramping capabilities. The recent advancements on the storage technology front have great potential in terms of applications to power systems for the second-by-second supply-demand balance – the so-called frequency regulation service. This service, also known by the technical term of automatic generation control (*AGC*) is absolutely essential to maintain the frequency of the power system at its nominal value. A particularly exciting development is the integration into the power system of storage devices known as flywheel energy storage (*FES*). These are compact structures that can range in output from 250 kW to 20 MW with a storage capability of up to 5 MWh. In this thesis, we investigate the effective utilization of *FES* for *AGC* service provision in the context of the competitive markets for such service.

The recent studies [1]-[4] investigated the benefit of fast storage for frequency regulation by performing the economic analysis and dynamic simulation of ancillary service markets and system operations. The studies indicate that fast storage is economically viable for frequency regulation. In addition, the grid benefits from the high ramping capabilities and the short response times of the regulation providers. In order to speed up the pace of storage adoption for the purposes of frequency regulation, the Department of Energy has funded several demonstration projects under the American Recovery and Reinvestment Act (*ARRA*). For example, Beacon Power with $24 million in funding from *ARRA* and $48 million of the total

project value, has designed and built the 20 MW and 5 MWh flywheel frequency regulation plant. The project is intended to put this technology on equal footing with conventional regulation providers by demonstrating the physical and economical feasibility of the flywheel technology [5]. The plant was commissioned in 2011 in the area of the NewYork ISO and so far demonstrates good economic and technical performance. To consolidate this achievement, in the beginning of 2013 Beacon Power started to build the flywheel regulation plant with the same parameters on the *PJM* footprint. The flywheel technology is acknowledged for its characteristics that make it attractive for the provision of frequency regulation service. Specifically, this technology can withstand harsh cyclic requirements of regulation. We can also identify following beneficial aspects of flywheels: fast response capability (the regulation storage resource based on flywheel technology is able to respond to any *AGC* signal command within its capacity limits), long life time, high round-trip efficiency of 95-98%, low maintenance costs and ease of siting.

The recent push for demonstration projects has been accompanied by a number of policy regulations, which goal is to further promote the use of storage technologies in frequency regulation provision. All wholesale electricity markets in the United States are overseen by the Federal Energy Regulatory Commission (*FERC*), an agency that ensures competitiveness and fairness for all parties, operating in the markets. The integration of new technologies into frequency regulation provision has been the subject of two *FERC* orders recently. The major stimulus for greater use of the storage came with the *FERC* Order No.755 released on October 20, 2011 [6]. Under this order, frequency regulation service providers must be compensated using a two-part tariff. The first part is a payment for capacity to operate under *AGC* signal, i.e., a unit must reserve a part of the output for regulation provision. The second part of frequency

regulation compensation is the performance payment that reflects the quantity of the up and down movements in response to the system operator's *AGC* dispatch signal. This part accounts for the fact that a fast-response resource with a higher ramping rate is more effective in providing regulation service than a slow-response resource with a low ramping capability and must be paid appropriately. Hence, *FERC* ensures that Order No. 755 results in more regulation being provided by technologies that are faster-responding to the *AGC* signal and more suitable to provide regulation service, while fewer conventional resources will participate in the market. Since resources that provide greater benefits to the grid are compensated appropriately, the implementation of Order No. 755 will lead to better market efficiency through alignment of performance and incentives.

The subsequent regulatory action indirectly affecting the integration of storage into frequency regulation is *FERC* Order No. 764 released on June 22, 2012 [7]. The order mandates to partition the day-ahead market (*DAM*) scheduling period into shorter-duration subperiods to facilitate the integration of *VER*s and energy-limited resources into energy and ancillary services markets. For the storage-based regulation suppliers this order is beneficial since it provides more flexibility in allocation of the stored energy in a most effective way.

The demonstration projects and policy initiatives had demonstrated that *FES* is a viable technology, which can provide regulation service into the grid. Such encouraging results raise a question of what is an effective deployment of *FES* technology for this purpose. This is a precise issue we address in the thesis. But, as a first step we discuss the salient aspects of the *AGC* service provision and review the current state of the art in the area of the frequency regulation service provision by storage devices, in general, and by *FES*, in particular. We then follow with a

description of the contribution made by the work reported here. Section 1.5 outlines the contents of this thesis.

## 1.2 The Salient Aspects of *AGC* Service Provision by Storage Technology

*AGC* service is implemented to control the output of several generators to maintain frequency within acceptable bounds and regulate the power interchange between control areas. *AGC* service is one of the ancillary services that are traded in electricity markets running by independent system operators (*ISO*s) and regional transmission organizations (*RTO*s). The *ISO*s and *RTO*s, referred in the thesis as independent grid operators (*IGO*s), purchase the frequency regulation service in the *DAM*s and real-time markets (*RTM*s) from suppliers which are able to respond to the *AGC* signal by varying their output according to the signal commands. By selling certain capacity bandwidth on regulation market, the unit operator implies the responsibility to vary the unit's output under *AGC* commands within this bandwidth. The scheduled capacity output that resulted from the outcome of energy *DAM*s clearing establishes the baseline rate of the unit providing *AGC* service. If the resource following the *AGC* commands raises its output above the baseline rate, it provides regulation up service. In contrast, if the unit lowers its output below baseline rate, it provides regulation down. The *IGO*s have different approaches in procurement of the regulation service. For example, *CAISO* procures up and down regulation as two separate products. On the other hand, *PJM* considers up and down regulation as a single product. In order to facilitate our discussion, we consider regulation in up and down directions as two separate products, which are traded separately. Under current policies, all *IGO*s prohibit the energy-limited resources from selling energy. Therefore, storage devices operate with zero

baseline rate, which implies that their generation mode is for the regulation up service provision and their load mode is for regulation down service.

### 1.3 Review of the State of the Art in Storage Utilization for Frequency Regulation

The question of how to utilize the storage for the frequency regulation service provision has been the subject of several papers. In this section we give a brief summary of the literature related to the utilization of storage resources in the frequency regulation service provision. A very useful and comprehensive survey paper assessing the storage utilization in the *AGC* service provision is by Ibraheem et al. [8].

The emergence of new storage technologies over the last two decades pushed the researchers to explore the technologies' compatibility for frequency regulation service provision. A number of papers and reports have outlined conceptually what storage technologies fit the requirements of *AGC* service [9]-[13]. For example, Gross and Guille have presented the conceptual framework of vehicle-to-grid (*V*2*G*) implementation and demonstrated its feasibility for regulation service provision [11]. The utilization of superconducting magnetic energy storage (*SMES*) for *AGC* is introduced in [10]. The recent advancements of battery technology enabled the conceptual development of large-scale storage facilities for *AGC* service provision, which has been analyzed in [9], [12], [13].

The large majority of the papers related to the *AGC* service provision by storage technologies discuss the modifications in control algorithms that allow accommodation of the limited capability of storage technologies [14]-[18]. The decentralized *AGC* concept deals with

storage facilities spread over distantly connected geographical territories [14]. The multilevel control concept is used to build a hierarchical structure in the usage of conventional and storage *AGC* providers [15].

There is a long history of work on using the fast-acting storage in conjunction with *VER* generation [19]-[24]. Thatte et al. proposed the scheme to coordinate wind generation and *FES* for a provision of grid frequency regulation service [19]. The scheme enables both wind generation and *FES* to collectively respond to the system frequency deviation. It is shown that this combination can effectively provide *AGC* service, however, under certain conditions the valuable wind generation can be spilled out due to the limited storage capability of the *FES*. The effect is also observed for aggregation with photovoltaic energy resources [20].

After restructuring, the storage facilities are operated as private entities by offering regulation capacities in *IGO*-run ancillary service markets. A number of works has focused on strategies to maximize profits from participating in the market [25]-[27]. Researchers from the Pacific Northwest National Laboratory have developed a method to generate the *DAM* offer schedule for a hybrid storage system, which includes fast-response *FES* and slow response hydro unit [25]. The strategy aims to maximize profit from energy and frequency regulation provision in the wholesale market. The Donadee and Ilic approach to generate the offers into the *DAM*s for frequency regulation and energy bids for charging the aggregated fleet of electric vehicles involves the stochastic co-optimization of these services [26]. Their scheme allows the provision of both up and down regulation services during the low-load conditions as they assume a non-zero baseline rate of charging. Hence, if aggregation charges with capacity lower than the baseline rate, then it provides regulation down service; in contrast, if aggregation charges with capacity above the baseline rate, it provides the regulation up service. Both [25] and [26] are

focused on offering services in hourly *DAM*s, but do not recognize the ample potential from participating in *RTM*s.

The deployment and successful operation of the *FES* in the *NYISO* markets provides researchers valuable data on *FES* performance in the frequency regulation provision. References [28]-[30] report the current practice of *FES* utilization, particularly by analyzing the key challenges and disadvantages associated with the *FES* technology. Engineers are careful to note that *FES* has a relatively low energy-to-power ratio, a situation that implies a clear restriction on its ability to provide frequency regulation over longer periods of time and one type of regulation needs. Figure 1.1 represents the regulation *AGC* signal requirements for a typical summer day of June 14, 2011 in *PJM* and the corresponding *FES* status during this day. The 20 MW and 5 MWh *FES* participates on hourly *DAM*s by offering its full capacity in up and down directions and is able to provide regulation only for 62% of the total 24 hours. The remaining time the *FES* was unable to respond to the *AGC* commands because it had hit the upper or the lower physical limit of the energy level. Vu, Masiello, et al. report an unavailability rate as high as 41% [28]. The effect is especially unfavorable because the unit cannot contribute regulation during high load conditions. The *IGO* has no choice but to procure regulation services from other resources to meet regulation requirements. In order to effectively accommodate the energy-limited regulation resources, *IGO*s are looking for other solutions.

There are several attempts to deal with the described limitation on *FES* performance. For example, *CAISO* is implementing the regulation energy management (*REM*) system for non-generating resources [31] participating in the regulation market. The *REM* is based on a smart grid system, which controls not only the capacity output of the unit, but also monitors the energy level of the storage device. Using the regulation requirements and energy level of each resource

that provides regulation service, *IGO* determines the appropriate *AGC* signal for each player and ensures nonviolation of energy limits. This approach allows for the improvement of the regulating units' performance, but some critics express concerns of grid reliability once the number of energy-limited regulation suppliers attains critical mass [32].

Until now there has been no work which investigates the advantageous characteristics of the real-time *AGC* service market and their possible utilization to improve the performance of regulation suppliers. Since the regulation service is a commodity now, deeper understanding of how to effectively exploit the market environment is needed.

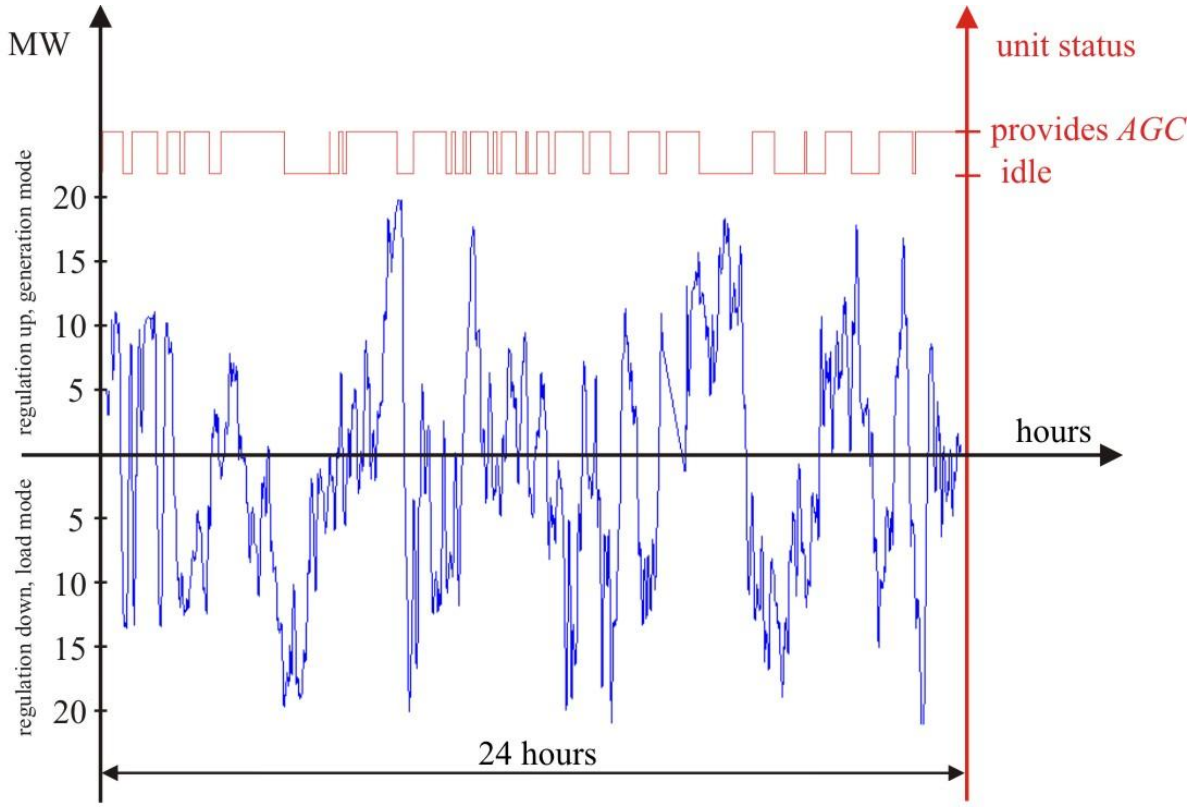


Figure 1.1: *PJM* regulation requirements and *FES* status on June 14, 2011

The regulation service is crucial for grid reliability, so that the issue of *FES* effective utilization is certainly of interest in the frequency regulation realm. We address in this thesis the solution approach of effective utilization of the *FES* in market environment. In Section 1.4 we summarize our proposed approach of effective utilization of the *FES* in the regulation service provision.

### 1.4 Scope and Contribution of the Thesis

In this thesis, we provide a comprehensive approach for the formulation of offers into the *DAM*s and *RTM*s with the express objective to effectively utilize *FES* for the provision of regulation service. In our studies we consider a single *FES* operated by an entity to offer regulation services into the *IGO*-run ancillary service markets. We have analyzed and employed the procedures established for storage resources participating in the ancillary service market to provide frequency regulation. We explicitly take into account the requirements of the recent *FERC* Orders No. 755 and No. 764.

Our work makes several contributions to the state-of-the-art. The developed approach of *FES* utilization for the frequency regulation provision allows the *FES* to provide reliable service into the grid. At the heart of our approach is the formulation of strategies with the objective to produce the offers into the hourly *DAM*s and the *RTM*s around the clock. The strategies are formulated as optimization programs with explicit representation of *FES* limited storage capability, response time and capacity limitations. Since the physical considerations are fully taken into account and the up-to-date information of *FES* time-varying variables is available for

the *RTM*s, the robust solution provides a reliable regulation service provision and can handle the inherent uncertainties in the *AGC* signals.

We demonstrate the capability of the developed approach through a number of case studies using *AGC* signal and year 2011price data from the *CAISO* and *PJM*. The test results indicate that the strategies formulated by the *FES* for the *DAM*s and *RTM*s are effective in ensuring full compliance with *AGC* signals sent by the *IGO*. Moreover, the effective utilization of the *FES* results in commensurate increase of *FES* monthly payment for frequency regulation service provision. In our sensitivity studies we investigate the impact of changing the duration of the cyclic offer pattern in *DAM*s and the impact of deployment of the risk-taking offer strategy on *RTM*. Another application of the proposed approach is to the analysis of the impacts of the policy changes promulgated by *FERC*. Specifically, we investigate the impact of the *FERC* Order No. 764 implementation, which mandates to partition hourly *DAM* periods into shorter subperiods.

The proposed approach for the formulation of offers into the *DAM*s and *RTM*s enables the *FES* operator to effectively utilize the regulation unit by providing reliable service in the grid. Furthermore, the implemented case studies can help the *FES* operator to quantify the range of benefits and limitations of *IGO*'s ancillary service market rules and frequency regulation service provision procedures.

## 1.5 Outline of the Thesis

The thesis consists of four additional chapters and three appendices. In Chapter 2 we provide a detailed description of the frequency regulation provision framework, which is

represented as a three-layer structure of the regulation service provision in the day-ahead and real-time markets, and the layer of physical operations under *AGC*.

In Chapter 3, we use the proposed framework to construct the *FES* strategies to offer in hourly *DAM*s and *RTM*s around the clock. First we provide a general mathematical statement of the *FES* offer strategy in hourly *DAM*s making use of the *DAM* market rules and timeline. We, next, exploit the regulation provision cyclic behavior to formulate the *DAM* strategy as a linear optimization program. After setting up the necessary assumptions, we construct the *FES* offer strategy into *RTM*s. We detail all the constraints, imposed as a result of the accepted offers into hourly *DAM*s and the preceding same hour *RTM*s, and by the limited physical capability of the *FES*.

In Chapter 4, we describe the results from representative case studies we have carried out using the proposed approach and actual 2011 data from the *CAISO* and *PJM*. In our studies, we investigate the impact of changing the duration of the cyclic offer pattern in *DAM*s and the impact of deployment of the risk-taking offer strategy on *RTM*. In this chapter, we also analyze the impacts of the policy changes promulgated by the *FERC*. Specifically, we investigate the impact of *FERC* Order No. 764 implementation, which mandates partitioning hourly *DAM* periods into shorter subperiods.

In Chapter 5, we summarize the results of our studies and point out directions for future work. Appendix A provides a summary of notations used in the thesis. In Appendix B, we give the procedure to calculate the *FES* payment for the regulation service provision, taking into account the requirements of *FERC* Order No. 755. In Appendix C, we provide a description of the *AGC* model, incorporated into the three-layer structure, and present an overview of the simulation approach.

# CHAPTER 2

# MODELING OF FREQUENCY REGULATION SERVICE AND CONSTRUCTION OF ANALYTIC FRAMEWORK

In this chapter we describe the development of the analytic framework, which we construct for the formulation of the strategies for *FES* participation in the two sets of markets – *DAM*s and *RTM*s. We start from the *FES* modeling to appropriately represent the physical characteristics of the unit, the impacts of the market rules and the unit response to the *AGC* signal under actual operating conditions. We continue with an overview of the framework structure which includes three layers and provide a detailed description of each layer.

## 2.1 The Three-Layer Framework of the Regulation Service Provision

The key objective of this chapter is to develop a framework capable to deal with all aspects of the regulation service provision by *FES* such as obligations imposed by participation in *DAM*s and *RTM*s and obligations to respond to *AGC* signals under real-time physical operations. In order to meet these objectives, a detailed representation of markets and *AGC* control is required. However, there is no single standard market design across the United States

and implementation of *AGC* control also varies. Therefore, in order to accommodate these differences, the framework must be stated on the most general basis.

The developed framework structure, as illustrated in Figure 2.1, has three layers – a layer for the offer formulation into the hourly *DAM*s (*DAM* layer), another layer for the additional offer formulation into *RTM*s (*RTM* layer) and a simulation layer of the *FES* operations in response to the *AGC* signals sent by the *IGO* to whose system the *FES* is interconnected (*AGC* physical operations layer). We interconnect these three layers by introducing the information flows to represent the interactions between the markets and actual operations under *AGC*. In order to appropriately represent these information flows in Section 2.2 we provide a detailed description of the *FES* model for the frequency regulation service provision.

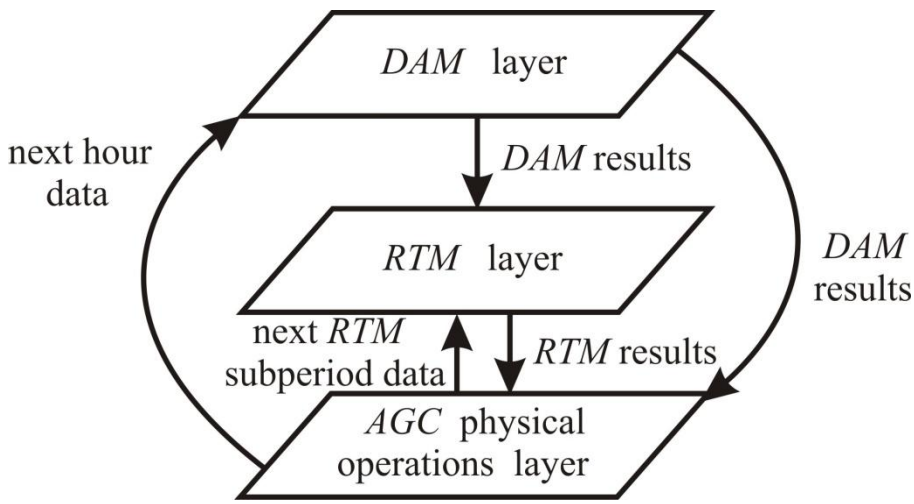


Figure 2.1: Three-layer structure of the framework

## 2.2 The *FES* Modeling for the Frequency Regulation Service Provision

We consider the parameters of the *FES* for the frequency regulation service provision. We denote by $r^M$ the maximal ramping rate of the unit. The ramping rate is a parameter provided

by themanufacturer to indicate the capacity increase/decrease per minute capability of the regulation unit. The ramping rate of *FES* is very high and can attain ±300 MW/min.

We next consider the storage capability of the storage regulation unit. We denote by $E^{M}$ the maximum storage capability of the *FES* in MWh. Based on the manufacturer's *FES* performance analysis, discharge of the *FES* to zero stored energy is not recommended, since this can exacerbate the unit's degradation. Therefore, we denote by $E^{m}$ the minimal level of stored energy the unit can be discharged to during the regulation service provision. The $p^{M,+}$ designates a maximum capacity of regulation up service and $p^{M,-}$ is a maximum capacity for regulation down service. Due to lack of operational experience with limited energy storage resources, the existing *IGO* market rules put certain restrictions on the ability of *FES* to offer energy into the *DAM* and *RTM*. As a result, the output base point of the *FES* for every time period is zero. The zero base point implies that the *FES* operates in generation mode for regulation up service provision and in load mode for regulation down service provision.

A convenient starting point for the *FES* modeling description is the *AGC* physical operations layer in which we embed the representation of *FES* operations in response to the *AGC* signals sent by the *IGO*. Figure 2.2 depicts the functional diagram of the *AGC* system. Frequency $f$ is measured and compared with the reference frequency $f_{ref}$ to generate a signal proportional to the frequency deviation $\Delta f$. A weighted value of this signal is added to the net tie-line interchange error $\Delta P_{tie}$ to produce the area control error (*ACE*) that corresponds to the power by which total generation must be changed in order to maintain frequency and the tie-line power interchange at the scheduled values [33]-[38]. The *ACE* value and *DAM*s and *RTM*s results from corresponding layers are input data to the energy management system (*EMS*) which defines the contribution of *FES* to the total frequency control service provision based on *RTM*s and *DAM*s clearing results and *FES* physical characteristics. The control algorithm of *EMS* broadcasts every $\sigma_n$ interval the specific *AGC* instruction with a command to raise or lower its power output. Analyzing the regulation service provision by *FES*, we consider the $\sigma_n$ interval as a smallest indecomposable unit of time, and no phenomena of shorter duration is considered in our study.

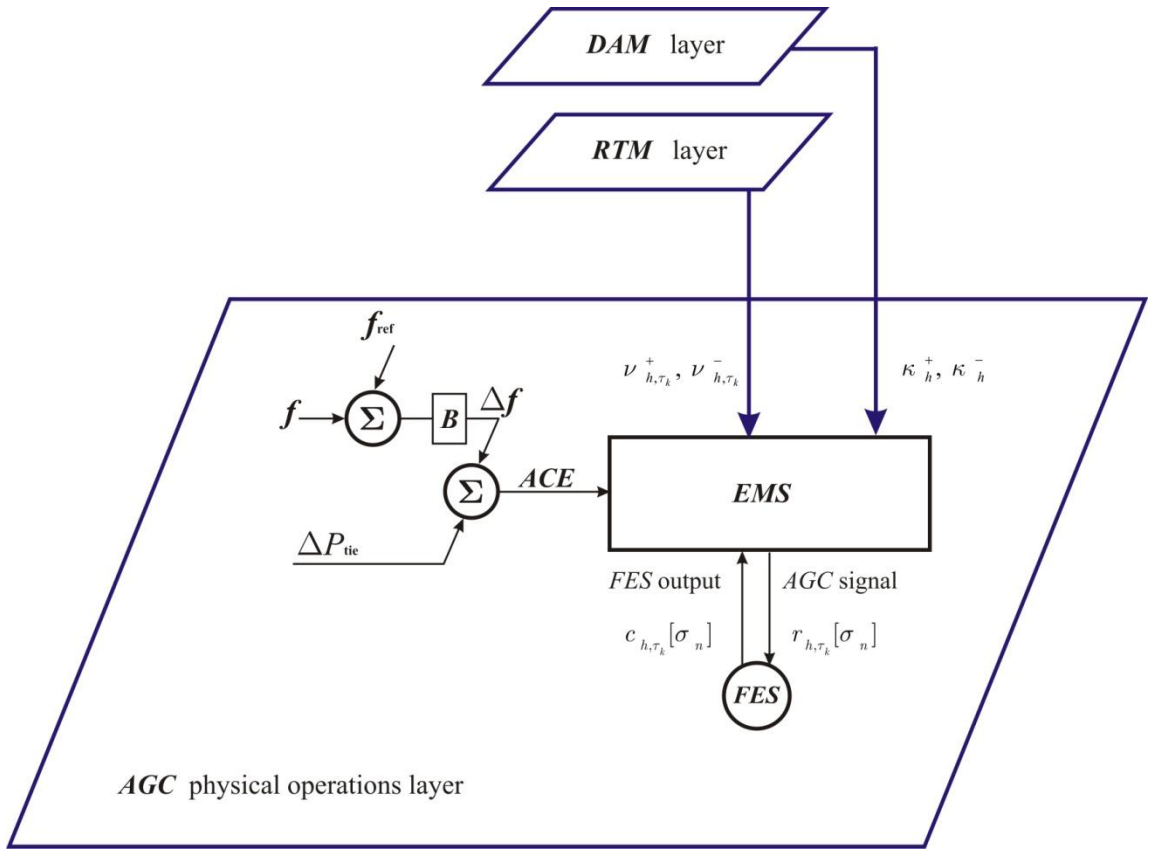


Figure 2.2: Functional diagram of the *AGC* system

We use $r_{h,\tau_k}[\sigma_n]$ to denote the *AGC* signal instruction. By the adopted convention, $r_{h,\tau_k}[\sigma_n]$ is positive when the regulation unit is instructed to increase generation and negative when it is instructed to lower generation. We also use $c_{h,\tau_k}[\sigma_n]$ to denote the actual power output of the *FES* at interval $\sigma_n$ of subperiod $\tau_k$ in hour *h*. By the same convention, the $c_{h,\tau_k}[\sigma_n] > 0$, when the unit injects energy into the grid (generator mode) and $c_{h,\tau_k}[\sigma_n] < 0$, when the unit withdraws energy (load mode). Therefore, the output $c_{h,\tau_k}[\sigma_n]$ in interval $\sigma_n$ is related to $c_{h,\tau_k}[\sigma_{n+1}]$ in interval $\sigma_{n+1}$ by:

$$c_{h,\tau_k}[\sigma_{n+1}] = c_{h,\tau_k}[\sigma_n] + \Delta c \tag{2.1}$$

$$\Delta c = \begin{cases} -\left| r_{h,\tau_k}[\sigma_n] \right| & \text{if} \quad r_{h,\tau_k}[\sigma_n] < 0 \\ r_{h,\tau_k}[\sigma_n] & \text{if} \quad r_{h,\tau_k}[\sigma_n] \geq 0 \end{cases}$$

Figure 2.3 depicts the functional diagram of the *FES* response to *AGC* signal instructions. We use $\varepsilon_{h,\tau_k}[\sigma_n]$ to denote the energy charge level at the end of interval $\sigma_n$ of subperiod $\tau_k$ in hour *h*. The output $\varepsilon_{h,\tau_k}[\sigma_n]$ at interval $\sigma_n$ is correlated with $\varepsilon_{h,\tau_k}[\sigma_{n+1}]$ at $\sigma_{n+1}$ as follows:

$$\varepsilon_{h,\tau_k}[\sigma_{n+1}] = \varepsilon_{h,\tau_k}[\sigma_n] + \frac{c_{h,\tau_k}[\sigma_n]}{NK} \tag{2.2}$$

Equations (2.1) and (2.2) establish the equations of motion of the *FES* unit under *AGC* control.

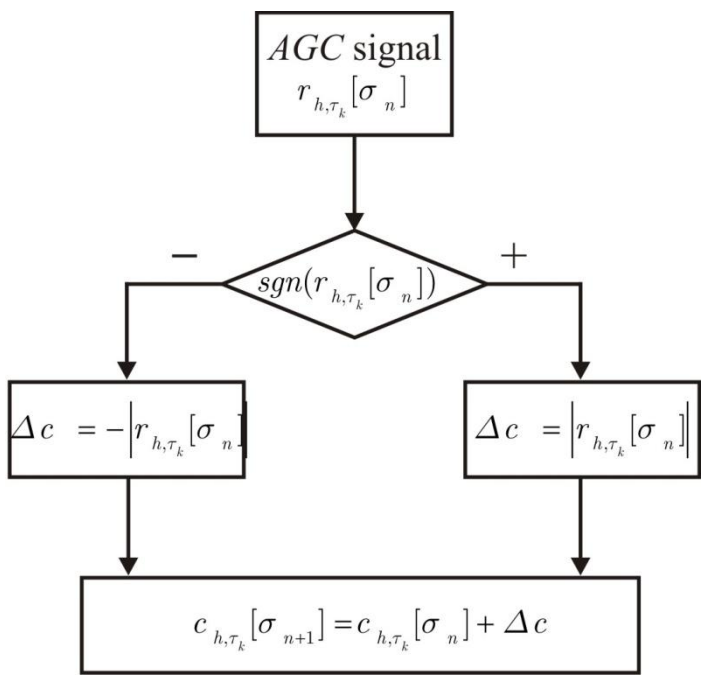


Figure 2.3: The *FES* response to *AGC* signal instructions

As discussed in Section 1.2, we consider regulation in the up and down directions as two separate products. Figure 2.4 represents an example of the *FES* providing regulation service for two hours by illustrating the capacity range over which the unit has to vary its output under the given *AGC* signal. The unit participates in regulation service provision and schedules to provide regulation up $\kappa_h^+$ and down $\kappa_h^-$ in hour *h* and regulation up $\kappa_{h+1}^+$ and down $\kappa_{h+1}^-$ in hour $h+1$. In other words, by providing regulation up service the seller assumes an obligation to vary its capacity output under the *AGC* signal between the zero base point and $\kappa_h^+$, and for regulation down between 0 and $-\kappa_h^-$. A similar statement is applicable to hour $h+1$. It is evident, that the *FES* is constrained by maximum capacity limits in generation $p^{M,+}$ and load $p^{M,-}$ modes.

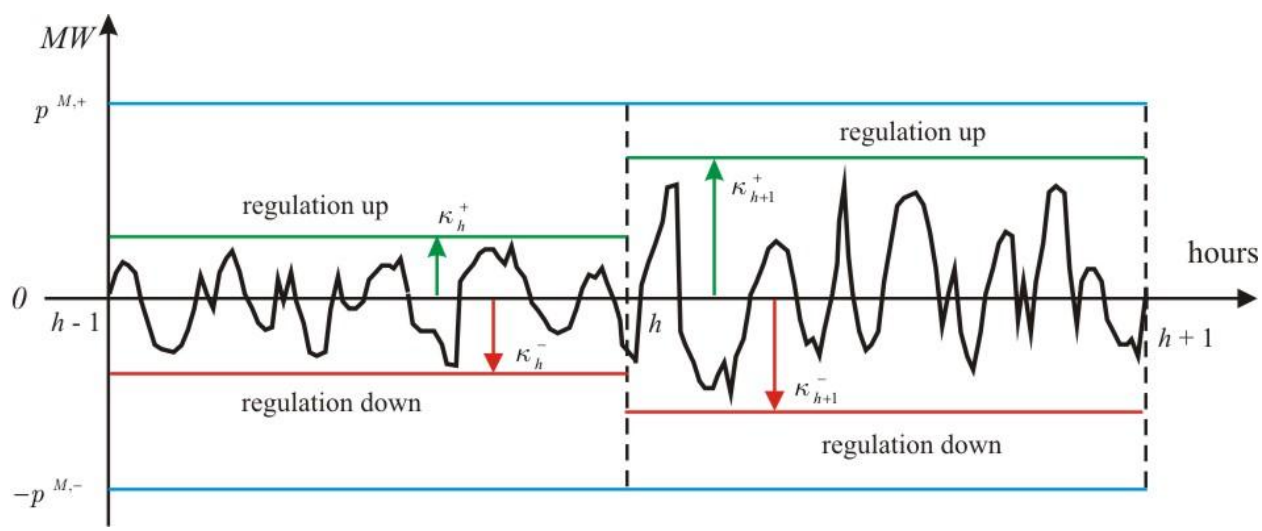


Figure 2.4: Regulation up and down service provision

After the electric power industry restructuring, frequency regulation became one of the ancillary services that must be procured on a competitive basis. Hence, the fleet of units participating in regulation is selected up on the clearing of the *DAM*s and *RTM*s using market mechanisms. In Sections 2.3 and 2.4 we analyze the frequency regulation provision in a market

environment by considering the *DAM* and *RTM* layers of the framework and focusing on offer formulation and dependence between two markets.

### 2.3 Layer for Offer Formulation into the Hourly *DAM*s

The regulation *DAM* is a capacity market operated by the *IGO*. Every *AGC* service seller indicates willingness to sell the service by submitting an offer to the *IGO*. Offers specify the sale quantities and prices. Unlike an energy market, where the demand is determined by equilibrium of demand and supply curves, the total regulation requirements for every hourly *DAM* are determined by *IGO* as a percentage of the total load forecast [39]-[40]. Figure 2.5 depicts the timeline of the regulation *DAM*. All sellers, willing to participate on *DAM*s of day *d*, must submit their offers for each hour *h* in day *d* by 10 a.m. of day $d-1$. Under existing market rules, the *IGO* determines the outcome of the *DAM* by co-optimizing energy and ancillary services markets so that energy, regulation and spinning reserve requirements are met in the most economic manner. At 12 p.m. of day $d-1$, the *IGO* informs all regulation sellers cleared to provide service about the uniform clearing prices and the awarded capacity. The participants cleared on the *DAM* have an obligation for provision of regulation between 12 a.m. and 11:59:59 p.m. of day *d*.

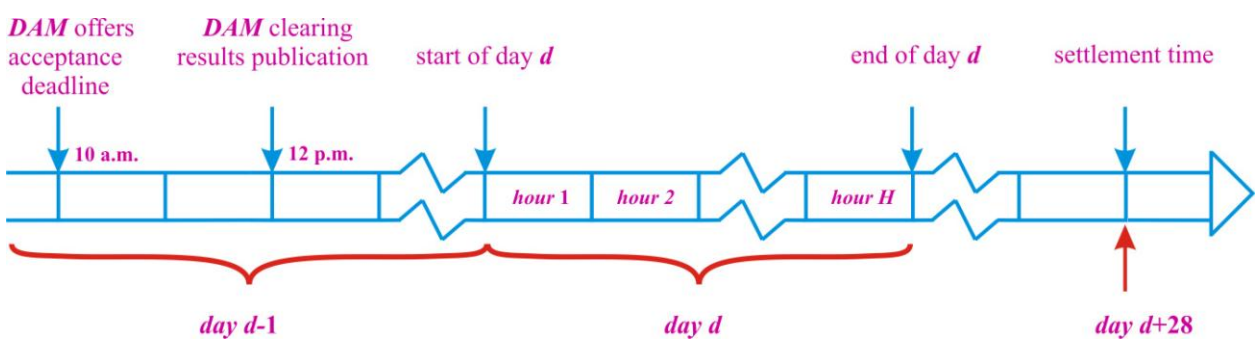


Figure 2.5: Regulation *DAM* timeline

By 10 a.m. on day $d-1$ the regulation service seller submits the offer decision $\hat{\beta}_h^d$ for every hour *h* in $\mathcal{H}$. In order to comply with *FERC* Order No. 755, which requires the *IGO* to account for the performance of the regulation provision, the offer $\hat{\beta}_h^d$ must include the following components and can be represented as

$$\hat{\beta}_h^d = \left\{ \left\{ \hat{\kappa}_h^+, \hat{\rho}_h^+ \right\}, \left\{ \hat{\kappa}_h^-, \hat{\rho}_h^- \right\}, \hat{\mu}_h \right\} \tag{2.3}$$

We denote by $\hat{\rho}_h^+$ ($\hat{\rho}_h^-$) the offer capacity price for regulation up (down) on *DAM* at hour *h*, and by $\hat{\mu}_h$ the offer mileage price on *DAM* at hour *h*. As a result of market clearing, every frequency regulation service provider receives back information regarding the capacities it is cleared to provide and capacity $\rho_h^+, \rho_h^-$ and mileage $\mu_h$ clearing prices, which are uniform for all cleared participants. *IGO* can clear not all the capacity offered for regulation but only part of it, so that following inequalities hold:

$$\kappa_h^+ \leq \hat{\kappa}_h^+$$

$$\kappa_h^- \leq \hat{\kappa}_h^-$$

Based on the market outcome information the seller is obligated to follow *AGC* instructions within an established capacity range, bounded by $\kappa_h^+$ and $\kappa_h^-$, and receive payment based on uniform clearing prices 28 days after the regulation service provision. The settlement scheme and equations to quantify the seller's payment are given in Appendix B.

### 2.4 Layer for Additional Offer Formulation into *RTM*s

Regulation *RTM* is a rolling market, run by *IGO* every subperiod $\tau_k$. The objective of regulation *RTM* is the procurement of additional regulation requirements arising in nearer-to-real- time operations. In this section we discuss the mechanics of regulation *RTM* we exploit in developing the formulation of the *RTM* offer strategy.

On a regulation *RTM* we define a subperiod $\tau_k$ to be a smallest indecomposable unit of time. We use a subscript $(h, \tau_k)$ after a variable to represent the subperiodic *RTM* quantities. According to each *IGO*'s rules, regulation service sellers indicate their willingness to participate on *RTM* by submitting the offer $\hat{\gamma}_{h,\tau_k}$, whose components are similar to the components of the offer into a *DAM* in (2.3), but apply to only interval $\tau_k$:

$$\hat{\gamma}_{h,\tau_k} = \left\{ \left\{ \hat{\nu}^{+}_{h,\tau_k}, \hat{\chi}^{+}_{h,\tau_k} \right\}, \left\{ \hat{\nu}^{-}_{h,\tau_k}, \hat{\chi}^{-}_{h,\tau_k} \right\}, \hat{\varphi}_{h,\tau_k} \right\}$$

The offer $\hat{\gamma}_{h,\tau_k}$ must be submitted during the subperiod $\tau_{k-2}$, as depicted on the *RTM* timeline shown in Figure 2.6. After *RTM* clearing, *IGO* publishes the information regarding clearing prices $\chi^{+}_{h,\tau_k}$, $\chi^{-}_{h,\tau_k}$, $\varphi_{h,\tau_k}$ and *FES* regulation capacity rewards $\nu^{+}_{h,\tau_k}, \nu^{-}_{h,\tau_k}$.

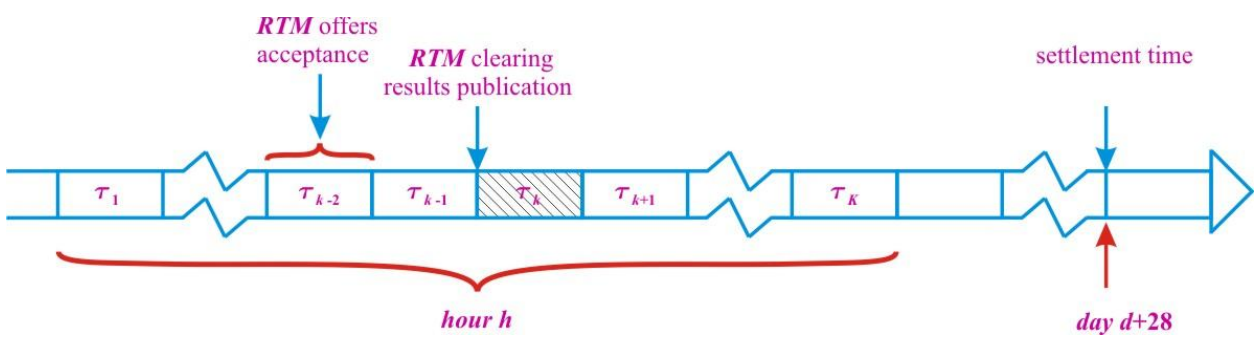


Figure 2.6: Regulation *RTM* timeline

The combined effect of cleared *DAM* and *RTM* results necessitates the addition of regulation capacities from both markets. We denote by $\delta^{\Sigma,+}_{h,\tau_k}$ ($\delta^{\Sigma,-}_{h,\tau_k}$) the combined regulation up (down) capacity on subperiod $\tau_k$ in hour *h*. Since the combined regulation capacity for each

individual regulation unit results from participating in both the *DAM* and the *RTM*, we define the combined regulation up capacity as

$$\delta^{+}_{h,\tau_k} = \kappa^{+}_{h} + \nu^{+}_{h,\tau_k}$$

and the combined regulation down capacity as

$$\delta^{-}_{h,\tau_k} = \kappa^{-}_{h} + \nu^{-}_{h,\tau_k}$$

To explain the concept, we provide a graphical diagram on Figure 2.7 to indicate the impact of the regulation up and down provision on both *DAM*s and *RTM*s. Regulation up $\kappa^{+}_{h}$ and down $\kappa^{-}_{h}$ capacities cleared on *DAM*s form the hour-long capacity range around a zero base point to operate under *AGC* signal. Additionally, every *RTM* subperiod the regulation resource is obligated to widen the capacity range for regulation up by $\nu^{+}_{h,\tau_k}$ and down by $\nu^{-}_{h,\tau_k}$ resulting from the accepted *RTM* offer.

According to the *IGO*'s market rules, the maximal combined offer is constrained by maximal capacity output of the unit in the generation and the load modes:

$$\hat{\kappa}^{+}_{h} \le p^{M,+} \; ; \hat{\kappa}^{-}_{h} \le p^{M,-}$$

$$\delta^{+}_{h,\tau_k} \le p^{M,+} \; ; \delta^{-}_{h,\tau_k} \le p^{M,-}$$

On the other hand, the minimal capacity offer for the regulation market is constrained by the minimal capacity offer in up $p^{m,+}$ and down $p^{m,-}$ directions, specified in *IGO*'s market rules:

$$\hat{\kappa}^{+}_{h} \ge p^{m,+}; \quad \hat{\kappa}^{-}_{h} \ge p^{m,-}$$

$$\hat{\nu}^{+}_{h,\tau_k} \ge p^{m,+}; \quad \hat{\nu}^{-}_{h,\tau_k} \ge p^{m,-}$$

For example, most *IGO*s do not accept regulation offers in either direction below 0.5 MW.

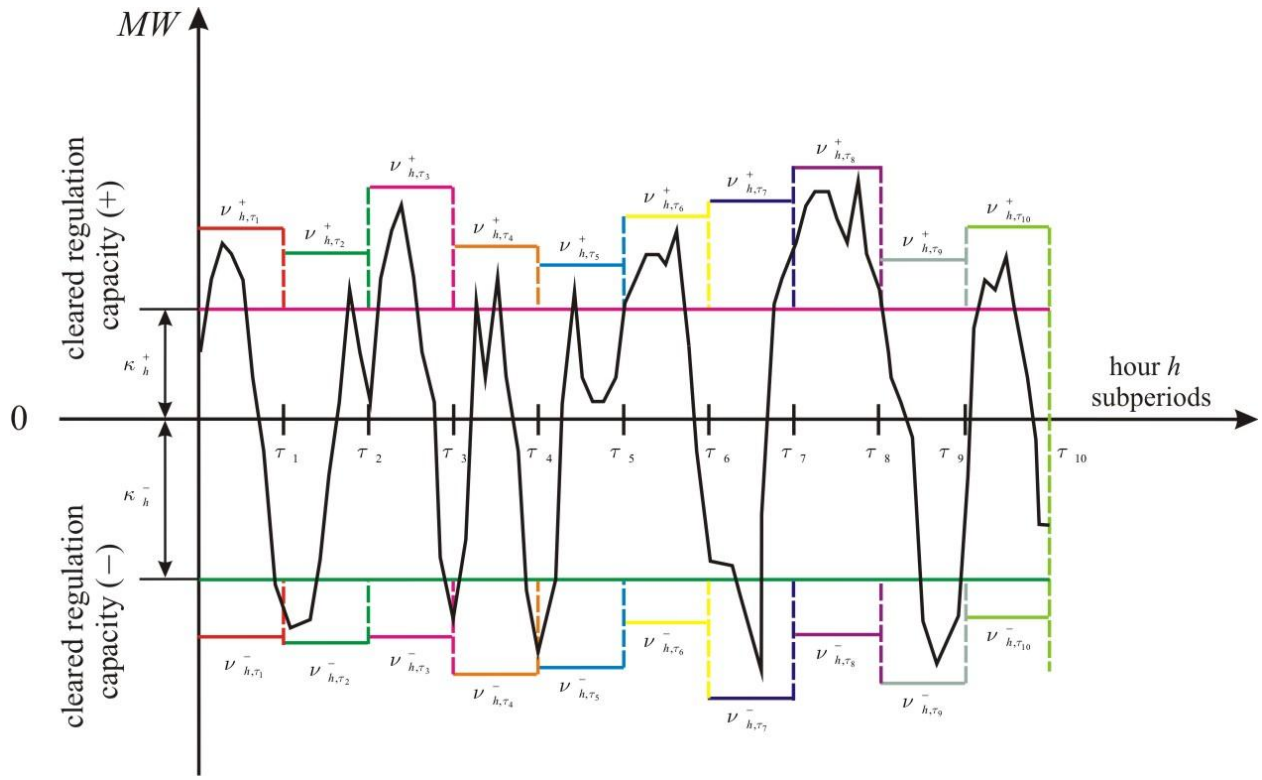


Figure 2.7: Combined *DAM* and *RTM* regulation capacity for 10 *RTM* subperiods of hour *h*

## 2.5 Summary

In this chapter we have developed the comprehensive framework for the offer strategies formulation in the two sets of markets – *DAM*s and *RTM*s. The framework incorporates the regulatory, financial and physical considerations of frequency regulation service provision by a *FES* unit, as well as their interactions, together with the analytical basis for the formulation of offers in compliance with the specified market rules. The developed framework structure has three layers – a layer for the offer formulation into the hourly *DAM*s, another layer for the additional offer formulation into the *RTM*s and a simulation layer of *FES* operations in response to the *AGC* signals sent by the system operator into whose system the *FES* is integrated. We have also discussed the *FES* modeling to appropriately represent the physical characteristics of the

unit, the impacts of the market rules and the unit response to the *AGC* signal under actual operating conditions.

# CHAPTER 3

# THE *FES* OFFER STRATEGY FORMULATION

In this chapter we apply the developed framework to construct the *FES* offer strategies formulation into the *DAM*s and *RTM*s. These two markets operate on different timescales, involve different levels of granularity, and differ in the time at which the market decisions are taken. Under these conditions, we may decouple the offer problem into two subproblems of offer regulation service on *DAM*s and *RTM*s independently. As a *FES* unit is a profit maximizing entity, the goal of the *FES* unit operator is to maximize the quantity of service provision so as to assure a steady stream of return on its investment. In order to meet objectives of *FES* participation in the frequency regulation market, the offer strategy formulations are stated as constraint optimization problems with a representation of the inter-temporal evolution of the storage in the *FES*.

The chapter contains three sections. In Section 3.1 we develop the offer strategy on hourly *DAM*s in most general terms and state it as a bilinear optimization problem. Next, in Section 3.2 we make use of periodicity of the frequency regulation provision cycle, so as the offer strategy is stated as a linear program. Section 3.3 presents the offer strategy on *RTM*.

### 3.1 Offer Regulation Service Strategy Formulation into the *DAM*s

In this section we provide a mathematical statement of the *FES* offer strategy formulation into the hourly *DAM*s making use of the *DAM* structure with the timeline as specified in Chapter 2.

By 10 a.m. of day $d-1$ the *FES* operator must make offer decision $\hat{\beta}_h$ for every hour *h* in $\mathcal{H}$. The determination of set $\left\{\hat{\beta}_h, \forall h \in \mathcal{H}\right\}$ consists of following steps:

1. determination of the hours when the *FES* has willingness to provide regulation service
2. determination of the type of regulation (up, down or both) to provide if the *FES* is willing to offer the service in that hour
3. determination of the capacity in MW for each regulation service in hour *h*
4. determination of capacity and mileage price offers for each regulation service in hour *h*

On a *DAM*, we consider an hour to be a smallest indecomposable unit of time. As such, if *FES* chooses to provide regulation in hour *h*, then it has to operate under the *AGC* signal during the entire hour *h*. We denote by $u_h$ the binary variable, which indicates the willingness to provide any regulation in hour *h*:

$$u_h = \begin{cases} 1 & \text{if } FES \text{ provides regulation service in hour } h \\ 0 & \text{otherwise} \end{cases}$$

Next, we denote by $u_h^+$ ($u_h^-$) the binary variable, indicating the willingness to provide regulation up (down) in hour *h*:

$$u_h^+ = \begin{cases} 1 & \text{if } FES \text{ provides regulation up service in hour } h \\ 0 & \text{otherwise} \end{cases}$$

$$u_h^- = \begin{cases} 1 & \text{if } FES \text{ provides regulation down service in hour } h \\ 0 & \text{otherwise} \end{cases}$$

We can establish the following relationships between these binary variables:

$$u_h = 1 \quad \Leftrightarrow \quad u_h^+ + u_h^- \geq 1$$

It indicates that if *FES* offers frequency regulation service at least in one direction then it is under *AGC* for the entire hour *h*. On the other hand, if *FES* does not offer any regulation, then it is not under *AGC* and can use this hour to offer the service into the *RTM*s and move its storage energy charge to a pre-specified value.

According to the *IGO*'s market rules, if a regulation provider offers *AGC* service into the *DAM* then the capacity must be greater than the minimum capacity offer in the up $p^{m,+}$ and down $p^{m,-}$ directions, which quantities are stipulated by *IGO*, and less than the *FES* physical upper capacity limit in charging $p^{M,-}$ and discharging $p^{M,+}$ modes. Hence, for those hours when *FES* offers any type of regulation on *DAM* ($u_h = 1$), we state the following capacity offer constraints and relate them to corresponding binary variables:

$$p^{m,+} \leq \hat{\kappa}_h^+ \leq p^{M,+} \quad \Leftrightarrow \quad u_h^+ = 1 \tag{3.1}$$

$$p^{m,-} \leq \hat{\kappa}_h^- \leq p^{M,-} \quad \Leftrightarrow \quad u_h^- = 1 \tag{3.2}$$

For an hour in which *FES* does not offer up (down) regulation service, the corresponding binary variable $u_h^+$ ($u_h^-$) is set equal to zero. The Figure 3.1 depicts the offer decision diagram.

Next, we discuss the energy constraints, imposed by the *FES* limited energy capability. Since the *AGC* signal indicates the demand-supply imbalance in real time, the actual shape of the *AGC* curve is not known ahead of its determination. Therefore, the *FES* operator does not have information of the exact value of stored energy at the end of an hour *h* when the unit offers regulation service. The energy constraints are specified in terms of the upper and lower bounds of the storage unit capability. We denote for the end of the hour *h* the upper and lower bounds of stored energy by $\overline{\overline{e}}_h$ and $\underline{\underline{e}}_h$, respectively. Moreover, if the unit does not offer the regulation service in hour *h DAM*, it uses this hour *h* to recharge the *FES* to pre-specified charge rate $e_h^0$.

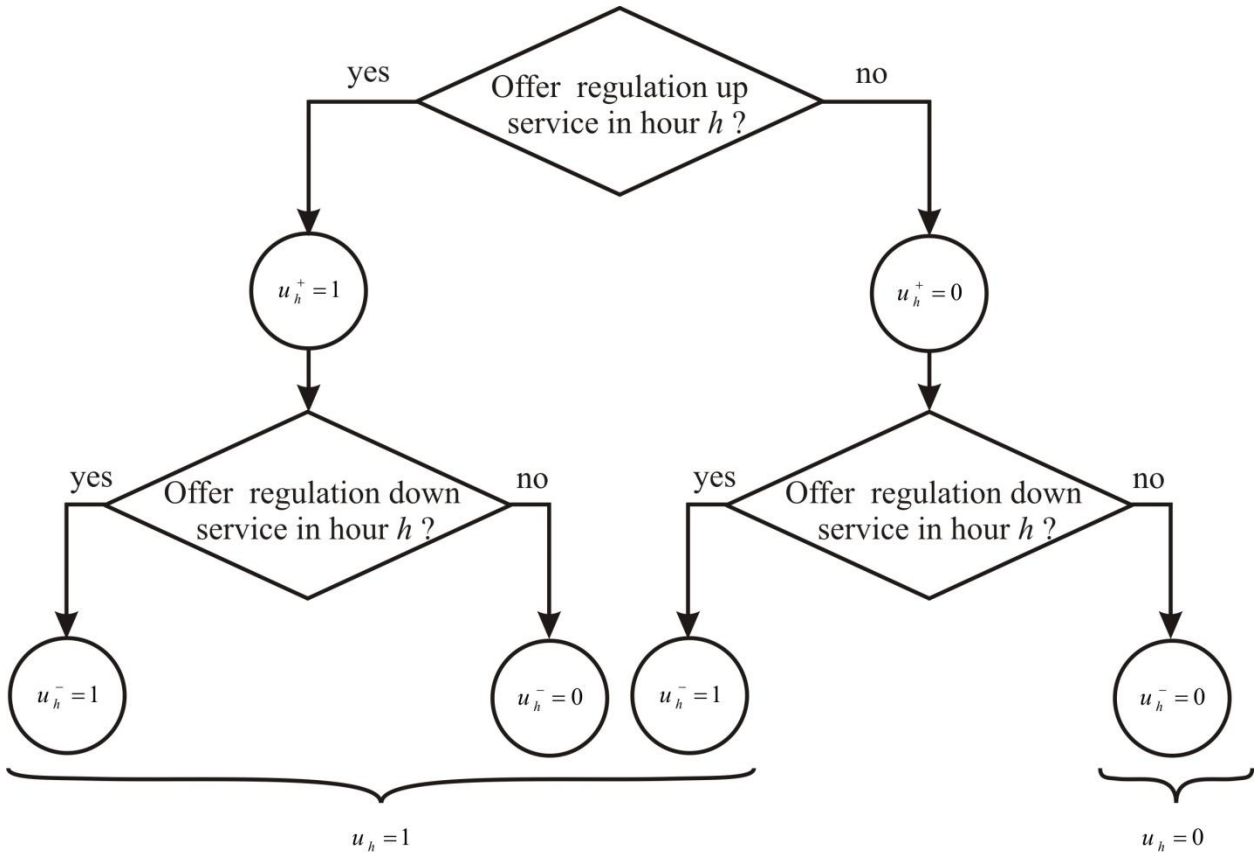


Figure 3.1: Offer decision-making diagram

To establish inter-hour relationships of *FES* energy charge, we need to consider all possible realizations of the *AGC* signal over the period of the offer. This task involves an enormous amount of work. In order to simplify the problem, we may only consider those *AGC* signal realizations which move the *FES* charge toward boundary conditions. Since the main feature of the proposed offer strategy is a *FES* guaranteed capability to provide regulation service under every possible realization of *AGC* signal, the boundary conditions of *AGC* can establish the *FES* energy charge bounds, hence, significantly simplifying the problem. Figure 3.2 depicts a possible *AGC* realization and the associated energy charge in the *FES* that results. The upper (lower) energy bound at the end of hour *h* is calculated based on assumption that unit was charging (discharging) with a capacity $\kappa_h^-$ ($\kappa_h^+$) during the entire hour *h*.

At the end of the hour *h*, during which the *FES* offers regulation capacity, the upper bound on its stored energy is determined under the assumption that the *AGC* signal commands the *FES* to provide regulation down service with capacity $\hat{\kappa}_h^-$ throughout the hour:

$$\overline{\overline{e}}_h = \overline{\overline{e}}_{h-1} + \hat{\kappa}_h^- \tag{3.3}$$

The lower bound of stored energy is determined under the analogous assumption that the *AGC* signal commands the *FES* to provide regulation up service with capacity $\hat{\kappa}_h^+$ throughout the hour:

$$\underline{\underline{e}}_h = \underline{\underline{e}}_{h-1} - \hat{\kappa}_h^+ \tag{3.4}$$

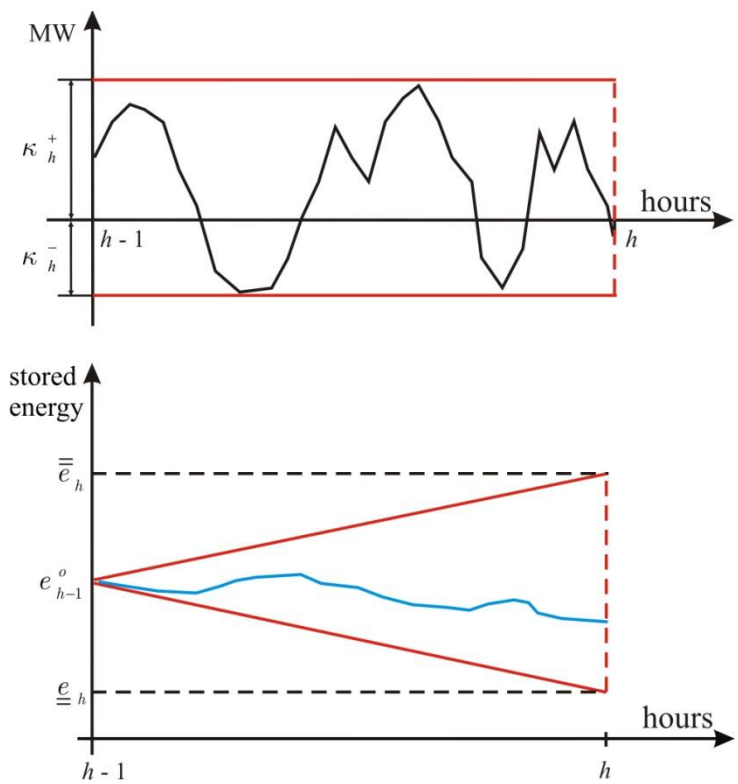


Figure 3.2: A possible *AGC* signal with its impact on the associated *FES* energy charge and the "worst-case" boundary limits

The equations (3.3) and (3.4) are applicable for the hour *h*, during which the *FES* provides regulation. For the case that the *FES* does not provide regulation service in hour *h*, the *FES* moves its stored energy to a pre-specified value $e_h^0$. To capture both these possibilities, we use binary variable $u_h$ in the energy constraint formulation, which introduces cross-hourly coupling in the hourly *DAM*s:

$$\overline{\overline{e}}_h = \left(\overline{\overline{e}}_{h-1} + \hat{\boldsymbol{\kappa}}_h^-\right) u_h + e_h^0 \left(1 - u_h\right)$$

$$\underline{\underline{e}}_h = \left(\underline{\underline{e}}_{h-1} + \hat{\boldsymbol{\kappa}}_h^+\right) u_h + e_h^0 \left(1 - u_h\right)$$

The hourly energy bounds are also constrained by the *FES*'s upper and lower physical energy storage limits:

$$\overline{\overline{e}}_h \le E^M$$
$$\underline{\underline{e}}_h \ge E^m$$

The objective of the offer problem is to maximize the *FES* revenues for the regulation service provision. As such, we formulate the objective function as follows:

$$f(\hat{\boldsymbol{\kappa}}_h^+, \hat{\boldsymbol{\kappa}}_h^-) = \sum_{h=1}^{H} \left( w_h^+ \hat{\boldsymbol{\kappa}}_h^+ + w_h^- \hat{\boldsymbol{\kappa}}_h^- \right)$$

where $w_h^+$ and $w_h^-$ are the weighting coefficients that reflect the hourly capacity prices of the day *d*, based on price forecasts or past historical data.

In summary, we denote the inter-hourly energy constrained *DAM* regulation service offer problem by $\mathcal{M}(\mathcal{H})$ and state it as follows:

$$\max_{\substack{\hat{\boldsymbol{\kappa}}_h^+, \hat{\boldsymbol{\kappa}}_h^-, u_h^+, u_h^-, \\ u_h, \overline{\overline{e}}_h, \underline{\underline{e}}_h}} \sum_{h=1}^{H} \left( w_h^+ \hat{\boldsymbol{\kappa}}_h^+ + w_h^- \hat{\boldsymbol{\kappa}}_h^- \right)$$

subject to

$$
\begin{aligned}
& p^{m,+} \le \hat{\kappa}_h^{+} \le p^{M,+} \qquad \Leftrightarrow \qquad u_h^{+} = 1 \\
& p^{m,-} \le \hat{\kappa}_h^{-} \le p^{M,-} \qquad \Leftrightarrow \qquad u_h^{-} = 1 \\
& \overline{\overline{e}}_h = \begin{cases} \overline{\overline{e}}_{h-1} + \hat{\kappa}_h^{-} & \text{if} \quad u_h = 1 \\ e_h^0 & \text{if} \quad u_h = 0 \end{cases} \\
& \underline{\underline{e}}_h = \begin{cases} \underline{\underline{e}}_{h-1} + \hat{\kappa}_h^{+} & \text{if} \quad u_h = 1 \\ e_h^0 & \text{if} \quad u_h^{+} = 0 \end{cases} \\
& \overline{\overline{e}}_h \le E^M \\
& \underline{\underline{e}}_h \ge E^m \\
& \overline{\overline{e}}_0 = \underline{\underline{e}}_0 = e_{1^-}^0
\end{aligned}
$$

The optimal solution to $\mathcal{M}(\mathcal{H})$ is specified by the set $\{u_h, \forall\, h \in \mathcal{H}\}$, which indicates the hours in which to regulation service is provided ($u_h = 1$) and the hours in which the *FES* does not participate in the regulation service provision ($u_h = 0$) so as to allow it to have the stored energy at the pre-specified value at the end of the hour *h*, the sets $\{u_h^{+}, \forall\, h \in \mathcal{H}\}$ and $\{u_h^{-}, \forall\, h \in \mathcal{H}\}$, which indicate the types of regulation service provided in each hour *h* in $\mathcal{H}$ in which the *FES* offers regulation service and the values of $\hat{\kappa}_h^{+}$ and $\hat{\kappa}_h^{-}$, which determine the offer amount in hour *h*. Note that all these quantities are the components of the set $\{\hat{\beta}_h, \forall h \in \mathcal{H}\}$. With regard to offer prices, we assume that each *FES* is a price taker and so submits offers with zero prices $\hat{\rho}_h^{+} = \hat{\rho}_h^{-} = 0$ and $\hat{\mu}_h = 0$ for $\forall h$ in $\mathcal{H}$. In addition, there are the associated sets $\{\overline{\overline{e}}_h, \forall\, h \in \mathcal{H}\}$ and $\{\underline{\underline{e}}_h, \forall\, h \in \mathcal{H}\}$ of upper and lower energy bounds for every hour *h* in $\mathcal{H}$. We use these sets to impose the energy constraints in the *RTM* offer problem formulation.

The problem statement above is in its general form and cannot be solved analytically as it involves the solution of a bilinear mixed-integer optimization problem and is intractable for $H = 24$. In Section 3.2 we make use of the salient characteristics of energy limited frequency regulation units and features of frequency regulation *DAM* to formulate a linear optimization problem and state the conditions to determine its optimal solution.

### 3.2 *DAM*s Regulation Offer Strategy Formulated as a Linear Program

In order to simplify the *DAM* offer problem $\mathcal{M}(\mathcal{H})$, we wish to exploit the fact that the alternation of $\xi$ hours when the unit provides regulation service in both the up and the down directions ($u_h = 1,\ \ h = 1, 2, ..., \xi$) and hour $\xi + 1$ when the unit does not participate in regulation provision ($u_{\xi+1} = 0$) constitutes a cycle. We provide in Figure 3.3 the graphical illustration of regulation service provision patterns for $\xi = 1, 2, ..., 5$ and the assumption that $H = 24$ is an hour in which the *FES* does not participate in the regulation service provision. The hours in which the *FES* provides regulation service are crosshatched. Each $\xi + 1$ hour cycle schedule has *FES* participation in the *DAM*s for the first $\xi$ hours and no participation in hour $\xi + 1$. Moreover, for the transition to the next-day *DAM*s, the *FES* does not participate in the hour 24 *DAM*. This latter constraint may shorten the last cycle duration. For example, for $\xi = 5$ the *FES* participates at the hours 1-5, 7-11, 13-17, 19-23. The *FES* does not participate in the hours 6, 12, 18 and 24.

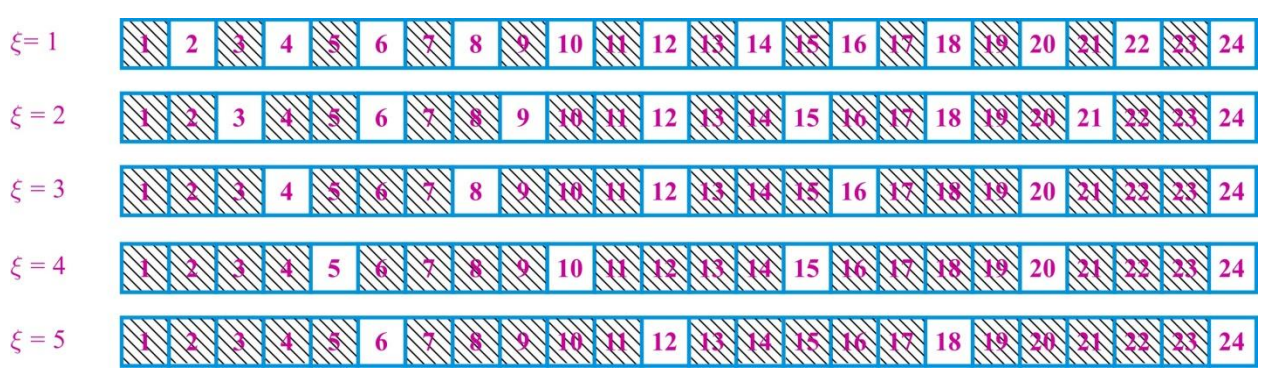


Figure 3.3 Regulation service provision patterns for $\xi = 1, 2, ..., 5$ with $H = 24$ designated as an hour for no participation in the regulation service

Based on initial charge $e_{1^-}^{0}$ at the beginning of the cycle and characteristics of *FES*, we can quantify the cycle of $\xi$ hours which guarantees at least minimum capacity offers $p^{m,+}$ and $p^{m,-}$ for every hour *h*. In other words, we need to choose a value for $\xi$ which ensures that the *FES* is capable of providing both types of regulation for the entire $\xi$ hours.

We use the following procedure to check the feasibility of $\xi$ for a given $e_{1^-}^{0}$:

1. Specify the upper and lower bounds of stored energy at the end of $\xi$ hours. If there are no other restrictions, we choose them to be an upper $E^{M}$ and lower $E^{m}$ energy limits of the regulation unit.
2. If $\xi > \dfrac{E^{M} - e_{1^-}^{0}}{p^{m,-}}$ or $\xi > \dfrac{e_{1^-}^{0} - E^{m}}{p^{m,+}}$, then $\xi$ is not feasible and any $\xi' > \xi$ is also not feasible.
3. If $\xi \le \dfrac{E^{M} - e_{1^-}^{0}}{p^{m,-}}$ and $\xi \le \dfrac{e_{1^-}^{0} - E^{m}}{p^{m,+}}$, then $\xi$ is feasible.

Once $\xi$ is determined, we next define the set $\mathcal{H}^{\xi}$ of the hours in which the *FES* participates in the offer of regulation service in the *DAM*:

$$\mathcal{H}^{\xi} = \left\{1, 2, \ldots, \xi, \xi+2, \ldots, 2\xi-1, 2\xi, 2\xi+2, \ldots, H-1\right\}$$

Now we can proceed to the statement of the optimization problem with the objective to maximize the capacity revenues over the set $\mathcal{H}^{\xi}$. We denote the inter-hourly energy constrained offer problem by $\mathcal{D}\left(\mathcal{H}^{\xi}\right)$ and state it as follows:

$$\max_{\hat{\kappa}_h^{+}, \hat{\kappa}_h^{-}, \bar{\bar{e}}_h, \underline{\underline{e}}_h} \sum_{h=1}^{\xi} \left( w_h^{+} \hat{\kappa}_h^{+} + w_h^{-} \hat{\kappa}_h^{-} \right)$$

subject to

$$
\begin{aligned}
& p^{m,-} \le \hat{\kappa}_h^- \\
& p^{m,+} \le \hat{\kappa}_h^+ \\
& \overline{\overline{e}}_h = \overline{\overline{e}}_{h-1} + \hat{\kappa}_h^{d,-} \\
& \underline{\underline{e}}_h = \underline{\underline{e}}_{h-1} - \hat{\kappa}_h^{d,+} \\
& \overline{\overline{e}}_h \le E^M \\
& \underline{\underline{e}}_h \ge E^m \\
& \overline{\overline{e}}_0 = \underline{\underline{e}}_0 = e_{1^-}^{\mathrm{o}}
\end{aligned}
$$

The optimal solution to $\mathcal{D}\left(\mathcal{H}^{\xi}\right)$ is specified by the set of the values of $\kappa_h^+$ and $\kappa_h^-$, which determine the offer amount into the *DAM* for $\forall h \in \mathcal{H}^{\xi}$, and the sets $\left\{\overline{\overline{e}}_h, \forall\, h \in \mathcal{H}^{\xi}\right\}$ and $\left\{\underline{\underline{e}}_h, \forall\, h \in \mathcal{H}^{\xi}\right\}$ of upper and lower energy bounds for every *h* in $\mathcal{H}^{\xi}$. The problem $\mathcal{D}\left(\mathcal{H}^{\xi}\right)$ is formulated as a linear program and, hence, can be easily solved by well-known methods.

### 3.3 Offer Regulation Service Strategy Formulation into the *RTM*s

In this section we develop the formulation of the *FES* offer strategy for regulation service in the *RTM*s associated with the hour *h DAM*. We employ the outcomes of the hour *h DAM* as the basis to determine the real-time offers into an associated *RTM*. Specifically, the *DAM* results establish constraints on the *FES* offers into an associated *RTM*. Given that the *DAM* capacity awards $\kappa_h^+$ and $\kappa_h^-$, we identify two distinct cases depending on the $\kappa_h^+$ and $\kappa_h^-$ values. The first case covers those hours $h \in \mathcal{H}^{\xi}$ in which the *FES* offer for regulation service is accepted in whole or in part. The second case is for the set $\mathcal{H}' = \left\{h,\ h \in \mathcal{H},\ h \notin \mathcal{H}^{\xi}\right\}$ in which the *FES* does not offer regulation service into the *DAM* and moves its charge to a specified value.

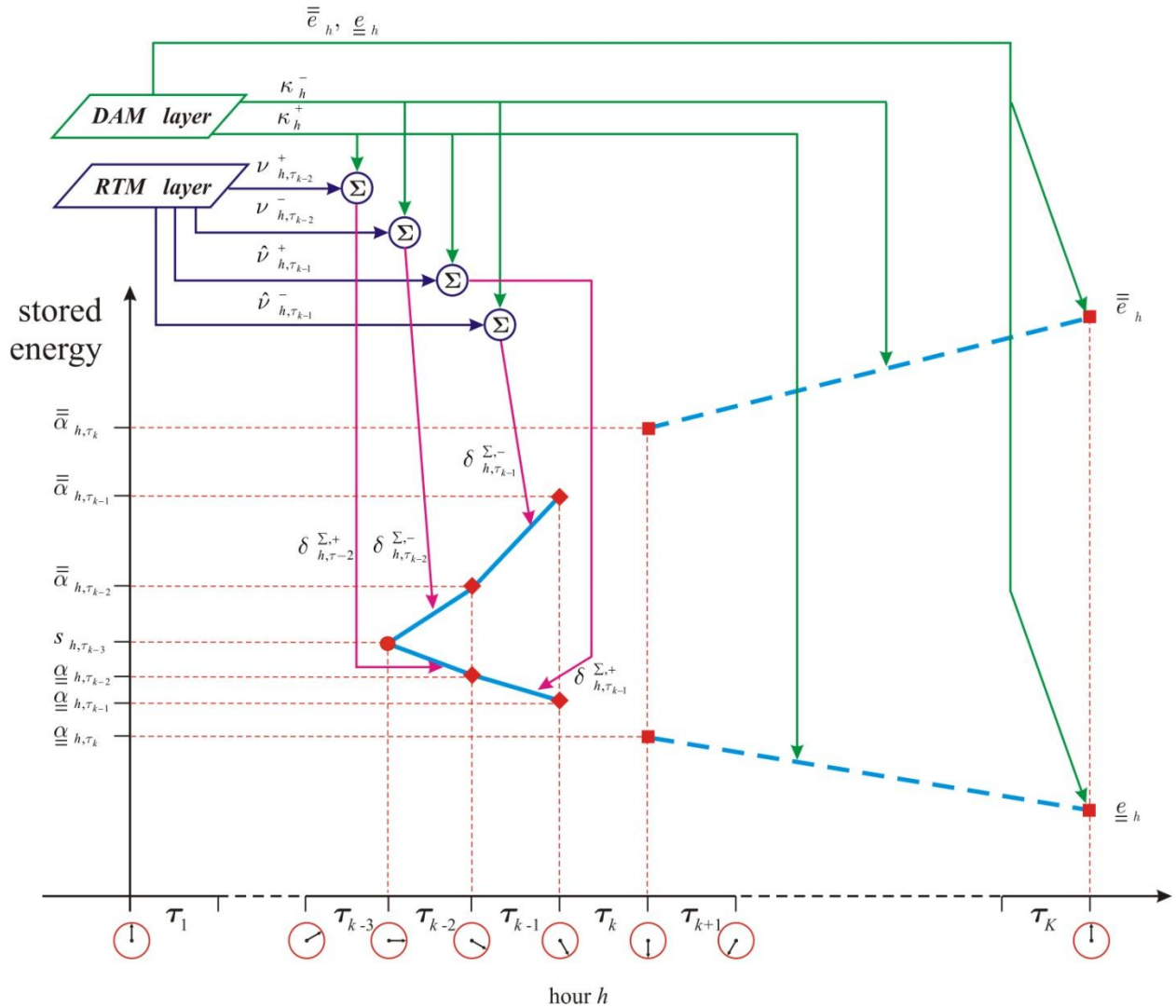


Figure 3.4: Energy constraints that must be satisfied in the formulation of the *RTM* offer

We consider first the formulation of the *RTM* offer strategy for hours $h \in \mathcal{H}^{\xi}$ and so the unit has the obligation to provide regulation service into the *DAM*. In light of the analysis of the *IGO* rules discussed in Section 2.4, we adopt the following offer protocols. The *FES* operator makes the offer decision $\hat{\gamma}_{h,\tau_k}$ for the subperiod $\tau_k$ of hour *h*, which must be submitted at the end of subperiod $\tau_{k-2}$, as shown in Figure 2.6. Similar to the offer strategy into the *DAM*s, we assume the regulation seller is a pricetaker in the *RTM*s and so submits the capacity and mileage prices to be

$$\hat{\chi}^{+}_{h,\tau_k} = \hat{\chi}^{-}_{h,\tau_k} = 0, \quad \hat{\varphi}_{h,\tau_k} = 0$$

In order to be able to submit the offer by the deadline, the *FES* operator starts to formulate its offer at the end of subperiod $\tau_{k-3}$, as indicated in Figure 2.6. At that time, the *FES* seller has the following information:

- energy charge $s_{h,\tau_{k-3}}$ at the end of subperiod $\tau_{k-3}$ in hour *h*
- the capacity awards after clearing the *hour h DAM*, specifically $\kappa^{+}_{h}$ and $\kappa^{-}_{h}$, which are constant over the entire hour *h*
- *RTM* awards $\nu^{+}_{h,\tau_{k-2}}$ and $\nu^{-}_{h,\tau_{k-2}}$ for subperiod $\tau_{k-2}$
- *FES* operator's capacity offers $\hat{\nu}^{+}_{h,\tau_{k-1}}$ and $\hat{\nu}^{-}_{h,\tau_{k-1}}$ for subperiod $\tau_{k-1}$
- the lower bound $\underline{\underline{e}}_{h}$ and the upper bound $\overline{\overline{e}}_{h}$ of the stored energy at the end of hour *h*

This information serves to formulate the following constraints (Figure 3.4):

- the allowed capacity range $\left[-\delta^{-}_{h,\tau_{k-2}};\ \delta^{+}_{h,\tau_{k-2}}\right]$ to participate in response to the *AGC* signals sent in the subperiod $\tau_{k-2}$ limits the combined *DAM* and *RTM* awards of either service

$$\delta^{+}_{h,\tau_{k-2}} = \kappa^{+}_{h} + \nu^{+}_{h,\tau_{k-2}}$$

$$\delta^{-}_{h,\tau_{k-2}} = \kappa^{-}_{h} + \nu^{-}_{h,\tau_{k-2}}$$

- at the end of subperiod $\tau_{k-3}$ the *RTM* for subperiod $\tau_{k-1}$ is unknown but the allowed capacity range $\left[-\delta^{-}_{h,\tau_{k-1}};\ \delta^{+}_{h,\tau_{k-1}}\right]$ to participate in response to the *AGC* signals during the subperiod $\tau_{k-1}$ limits the combined *DAM* award and the *RTM* offer amount in period $\tau_{k-1}$:

$$\delta^{-}_{h,\tau_{k-1}} = \kappa^{-}_{h} + \hat{\nu}^{-}_{h,\tau_{k-1}}$$

$$\delta^{+}_{h,\tau_{k-1}} = \kappa^{+}_{h} + \hat{v}^{+}_{h,\tau_{k-1}}$$

- the lower and upper bounds of the stored energy in the subperiod $\tau_{k-2}$ in terms of the charge $s_{h,\tau_{k-3}}$ and the combined capacity awards for up service $\delta^{+}_{h,\tau_{k-2}}$ and down service $\delta^{-}_{h,\tau_{k-2}}$ regulation in subperiod $\tau_{k-2}$:

$$\underline{\underline{\alpha}}_{h,\tau_{k-2}} \le s_{h,\tau_{k-2}} \le \overline{\overline{\alpha}}_{h,\tau_{k-2}}$$

$$\underline{\underline{\alpha}}_{h,\tau_{k-2}} \le s_{h,\tau_{k-3}} - \frac{\delta^{+}_{h,\tau_{k-2}}}{K}$$

$$\overline{\overline{\alpha}}_{h,\tau_{k-2}} \ge s_{h,\tau_{k-3}} + \frac{\delta^{-}_{h,\tau_{k-2}}}{K}$$

- the lower and upper bounds of the stored energy in the subperiod $\tau_{k-1}$ in terms of the period $\tau_{k-2}$ bounds $\underline{\underline{\alpha}}_{h,\tau_{k-2}} \le s_{h,\tau_{k-2}} \le \overline{\overline{\alpha}}_{h,\tau_{k-2}}$, the combined *DAM* award and period $\tau_{k-1}$ accepted *RTM* offer:

$$\underline{\underline{\alpha}}_{h,\tau_{k-1}} \le s_{h,\tau_{k-1}} \le \overline{\overline{\alpha}}_{h,\tau_{k-1}}$$

$$\underline{\underline{\alpha}}_{h,\tau_{k-1}} \le \underline{\underline{\alpha}}_{h,\tau_{k-2}} - \frac{\delta^{+}_{h,\tau_{k-1}}}{K}$$

$$\overline{\overline{\alpha}}_{h,\tau_{k-1}} \ge \overline{\overline{\alpha}}_{h,\tau_{k-2}} + \frac{\delta^{-}_{h,\tau_{k-1}}}{K}$$

- the lower and upper bounds of the stored energy in the subperiod in terms of the allocated energy range restricted by $\underline{\underline{e}}_{h}$ and $\overline{\overline{e}}_{h}$ in hour *h* and the obligations entailed by the hour *h DAM* clearing results taking into account that there are $K-k$ remaining subperiods in hour *h*:

$$\underline{\underline{\alpha}}_{h,\tau_{k}} \le s_{h,\tau_{k}} \le \overline{\overline{\alpha}}_{h,\tau_{k}}$$

$$\underline{\underline{\alpha}}_{h,\tau_{k}} \ge \underline{\underline{e}}_{h} + \frac{(K-k)}{K}\kappa^{+}_{h}$$

$$\overline{\overline{\alpha}}_{h,\tau_{k}} \le \overline{\overline{e}}_{h} - \frac{(K-k)}{K}\kappa^{-}_{h}$$

- the constraints imposed by the upper and the lower stored energy bounds in the subperiods $\tau_k$ and $\tau_{k-1}$ on the real-time offers $\hat{v}^{-}_{h,\tau_k}$ and $\hat{v}^{+}_{h,\tau_k}$:

$$\bar{\bar{\alpha}}_{h,\tau_k} - \bar{\bar{\alpha}}_{h,\tau_{k-1}} \geq \frac{\kappa^{-}_{h} + \hat{v}^{-}_{h,\tau_k}}{K}$$

$$\underline{\underline{\alpha}}_{h,\tau_{k-1}} - \underline{\underline{\alpha}}_{h,\tau_k} \geq \frac{\kappa^{+}_{h} + \hat{v}^{+}_{h,\tau_k}}{K}$$

- the impacts of the constraints of the *FES* maximum capacity output in the charging and discharging modes $p^{M,+}$ and $p^{M,-}$, respectively, and those of the minimum capacity offer $p^{m,+}$ and $p^{m,-}$:

$$\kappa^{-}_{h} + \hat{v}^{-}_{h,\tau_k} \leq p^{M,-}$$

$$\kappa^{+}_{h} + \hat{v}^{+}_{h,\tau_k} \leq p^{M,+}$$

$$p^{m,+} \leq \hat{v}^{+}_{h,\tau_k}$$

$$p^{m,-} \leq \hat{v}^{-}_{h,\tau_k}$$

We denote the formulation of the *DAM* outcome constrained *RTM* offer problem for subperiod $\tau_k$ in hour $h \in \mathcal{H}^{\xi}$ as $\mathcal{R}_{h \in \mathcal{H}^{\xi}}(\tau_k)$ and state it as follows:

$$\max_{\substack{\hat{v}^{+}_{h,\tau_k},\ \hat{v}^{-}_{h,\tau_k},\ \underline{\underline{\alpha}}_{h,\tau_{k-2}},\ \bar{\bar{\alpha}}_{h,\tau_{k-2}},\\ \underline{\underline{\alpha}}_{h,\tau_{k-1}},\ \bar{\bar{\alpha}}_{h,\tau_{k-1}},\ \underline{\underline{\alpha}}_{h,\tau_k},\ \bar{\bar{\alpha}}_{h,\tau_k}}} \quad \hat{v}^{+}_{h,\tau_k} + \hat{v}^{-}_{h,\tau_k}$$

subject to

$$
\begin{aligned}
\underline{\underline{\alpha}}_{h,\tau_{k-2}} &\leq s_{h,\tau_{k-3}} - \frac{\kappa_h^+ + \nu_{h,\tau_{k-2}}^+}{K} \\
\overline{\overline{\alpha}}_{h,\tau_{k-2}} &\geq s_{h,\tau_{k-3}} + \frac{\kappa_h^- + \nu_{h,\tau_{k-2}}^-}{K} \\
\underline{\underline{\alpha}}_{h,\tau_{k-1}} &\leq \underline{\underline{\alpha}}_{h,\tau_{k-2}} - \frac{\kappa_h^+ + \nu_{h,\tau_{k-1}}^+}{K} \\
\overline{\overline{\alpha}}_{h,\tau_{k-1}} &\geq \overline{\overline{\alpha}}_{h,\tau_{k-2}} + \frac{\kappa_h^- + \nu_{h,\tau_{k-1}}^-}{K} \\
\underline{\underline{\alpha}}_{h,\tau_k} &\geq \underline{\underline{e}}_h + \frac{(K-k)}{K}\kappa_h^+ \\
\overline{\overline{\alpha}}_{h,\tau_k} &\leq \overline{\overline{e}}_h - \frac{(K-k)}{K}\kappa_h^- \\
\overline{\overline{\alpha}}_{h,\tau_k} - \overline{\overline{\alpha}}_{h,\tau_{k-1}} &\geq \frac{\kappa_h^- + \hat{\nu}_{h,\tau_k}^-}{K} \\
\underline{\underline{\alpha}}_{h,\tau_{k-1}} - \underline{\underline{\alpha}}_{h,\tau_k} &\geq \frac{\kappa_h^+ + \hat{\nu}_{h,\tau_k}^+}{K} \\
\kappa_h^- + \hat{\nu}_{h,\tau_k}^- &\leq p^{M,-} \\
\kappa_h^+ + \hat{\nu}_{h,\tau_k}^+ &\leq p^{M,+} \\
p^{m,+} &\leq \hat{\nu}_{h,\tau_k}^+ \\
p^{m,-} &\leq \hat{\nu}_{h,\tau_k}^-
\end{aligned}
$$

The optimal solution to $\mathcal{R}_{h \in \mathcal{H}^{\xi}}(\tau_k)$ is specified by the set of the values of $\hat{\nu}_{h,\tau_k}^+$ and $\hat{\nu}_{h,\tau_k}^-$, which determine the offer amount into the *RTM* for subperiod $\tau_k$ of hour $h \in \mathcal{H}^{\xi}$.

We next consider the *RTM* offer strategy for the hours $h \in \mathcal{H}'$, in which the unit does not participate in the offer of regulation service into the *DAM*s. Rather, in such hours, the *FES* moves its charge to be at a pre-specified value of $e_h^0$. The *RTM* regulation timeline is the same as depicted in Figure 2.6. A significant advantage of flywheel technology is the relatively high ramping rate and so the *FES* can charge or discharge to attain a pre-specified value $e_h^0$ within no more than a few real-time subperiods. We denote by $\omega$ the number of real-time subperiods, used by the *FES* to charge or discharge. For the remaining $K - \omega$ subperiods of hour $\xi + 1$ in the cycle, the *FES* may participate in regulation service provision and so offers its capacity into those *RTM*s without being constrained by the hour $\xi + 1$ *DAM* clearing outcomes. Moreover, the

*FES* regulation *RTM* offer for subperiod $\tau_k$ is constrained only by the obligations to provide service in the preceding subperiods $\tau_{k-1}$ and $\tau_{k-2}$. These facts allow us to formulate the following constraints:

- the lower and upper bounds of the stored energy in the subperiod $\tau_{k-2}$ in terms of the charge $s_{h,\tau_{k-3}}$ and the real-time capacity awards for up service $\nu^{+}_{h,\tau_{k-2}}$ and down service $\nu^{-}_{h,\tau_{k-2}}$ regulation in subperiod $\tau_{k-2}$:

$$\underline{\underline{\alpha}}_{h,\tau_{k-2}} \leq s_{h,\tau_{k-3}} - \frac{\nu^{+}_{h,\tau_{k-2}}}{K}$$

$$\overline{\overline{\alpha}}_{h,\tau_{k-2}} \geq s_{h,\tau_{k-3}} + \frac{\nu^{-}_{h,\tau_{k-2}}}{K}$$

- the lower and upper bounds of the stored energy in the subperiod $\tau_{k-1}$ in terms of the period $\tau_{k-2}$ bounds $\underline{\underline{\alpha}}_{h,\tau_{k-2}} \leq s_{h,\tau_{k-2}} \leq \overline{\overline{\alpha}}_{h,\tau_{k-2}}$ and submitted *RTM* offer in subperiod $\tau_{k-1}$:

$$\underline{\underline{\alpha}}_{h,\tau_{k-1}} \leq \underline{\underline{\alpha}}_{h,\tau_{k-2}} - \frac{\hat{\nu}^{+}_{h,\tau_{k-1}}}{K}$$

$$\overline{\overline{\alpha}}_{h,\tau_{k-1}} \geq \overline{\overline{\alpha}}_{h,\tau_{k-2}} + \frac{\hat{\nu}^{-}_{h,\tau_{k-1}}}{K}$$

- the lower and upper bounds of the stored energy in the subperiod in terms of the physical energy limits of the *FES* taking into account that there is no *DAM* clearing in hour $\xi + 1$:

$$\underline{\underline{\alpha}}_{h,\tau_k} \leq s_{h,\tau_k} \leq \overline{\overline{\alpha}}_{h,\tau_k}$$

$$\underline{\underline{\alpha}}_{h,\tau_k} \geq E^{m}$$

$$\overline{\overline{\alpha}}_{h,\tau_k} \leq E^{M}$$

- the constraints imposed by the upper and the lower stored energy bounds in the subperiods $\tau_k$ and $\tau_{k-1}$ on the real-time offers $\hat{\nu}^{-}_{h,\tau_k}$ and $\hat{\nu}^{+}_{h,\tau_k}$:

$$\bar{\bar{\alpha}}_{h,\tau_k} - \bar{\bar{\alpha}}_{h,\tau_{k-1}} \geq \frac{\hat{v}^{-}_{h,\tau_k}}{K}$$

$$\underline{\underline{\alpha}}_{h,\tau_{k-1}} - \underline{\underline{\alpha}}_{h,\tau_k} \geq \frac{\hat{v}^{+}_{h,\tau_k}}{K}$$

We denote the formulation of the *RTM* offer problem for subperiod $\tau_k$ in hour $h \in \mathcal{H}'$ as $\mathcal{R}_{h \in \mathcal{H}'}(\tau_k)$ and state it as follows:

$$\max_{\substack{\hat{v}^{+}_{h,\tau_k}, \hat{v}^{-}_{h,\tau_k}, \underline{\underline{\alpha}}_{h,\tau_{k-2}}, \bar{\bar{\alpha}}_{h,\tau_{k-2}}, \\ \underline{\underline{\alpha}}_{h,\tau_{k-1}}, \bar{\bar{\alpha}}_{h,\tau_{k-1}}, \underline{\underline{\alpha}}_{h,\tau_k}, \bar{\bar{\alpha}}_{h,\tau_k}}} \quad \hat{v}^{+}_{h,\tau_k} + \hat{v}^{-}_{h,\tau_k}$$

subject to

$$\begin{aligned}
\underline{\underline{\alpha}}_{h,\tau_{k-2}} &\leq s_{h,\tau_{k-3}} - \frac{v^{+}_{h,\tau_{k-2}}}{K} \\
\bar{\bar{\alpha}}_{h,\tau_{k-2}} &\geq s_{h,\tau_{k-3}} + \frac{v^{-}_{h,\tau_{k-2}}}{K} \\
\underline{\underline{\alpha}}_{h,\tau_{k-1}} &\leq \underline{\underline{\alpha}}_{h,\tau_{k-2}} - \frac{\hat{v}^{+}_{h,\tau_{k-1}}}{K} \\
\bar{\bar{\alpha}}_{h,\tau_{k-1}} &\geq \bar{\bar{\alpha}}_{h,\tau_{k-2}} + \frac{\hat{v}^{-}_{h,\tau_{k-1}}}{K} \\
\bar{\bar{\alpha}}_{h,\tau_k} - \bar{\bar{\alpha}}_{h,\tau_{k-1}} &\geq \frac{\hat{v}^{-}_{h,\tau_k}}{K} \\
\underline{\underline{\alpha}}_{h,\tau_{k-1}} - \underline{\underline{\alpha}}_{h,\tau_k} &\geq \frac{\hat{v}^{+}_{h,\tau_k}}{K} \\
\underline{\underline{\alpha}}_{h,\tau_k} &\geq E^{m} \\
\bar{\bar{\alpha}}_{h,\tau_k} &\leq E^{M}
\end{aligned}$$

The optimal solution to $\mathcal{R}_{h \in \mathcal{H}'}(\tau_k)$ is specified by the set of the values of $\hat{v}^{+}_{h,\tau_k}$ and $\hat{v}^{-}_{h,\tau_k}$, which determine the offer amount into the *RTM* for subperiod $\tau_k$ in hours $h \in \mathcal{H}'$.

## 3.4 Summary

In this chapter we have introduced the formulation of the offer strategies for the regulation service provision into the *DAM*s and the *RTM*s. The statement of the formulation may be expressed as a linear program with the explicit representation of the inter-temporal evolution of the storage in the *FES*. The solution approach for this optimization problem makes extensive use of robust optimization concepts to determine the offer amounts of up and down regulation to service in each market for its corresponding period. These solutions provide conservative results under which both up and down regulation can be provided with 100% guarantee, independent of what the *AGC* signal turns out to be and taking into account the most up-to-date information on unit status up to the time an offer must be submitted. In Chapter 4, we apply this approach to obtain via simulation the results of representative studies in order to quantify the economics of the *FES* participation in the regulation service provision.

# CHAPTER 4

# CASE STUDIES

We devote this chapter to demonstrate the capability of the *DAM* and *RTM* offer strategy formulation approach and quantify the improved performance over current techniques through various case studies using actual 2011 *AGC* signal and price data from two large systems – the *CAISO* and *PJM*. Our studies include the investigations of the impacts of changing the duration of the cyclic offer pattern into the *DAM*s. We also study the impacts of the deployment of risk-taking offer strategies into the *RTM*s. A very insightful application of the proposed approach is the analysis of policy issue impacts. We illustrate such an application through a study of the changes promulgated by *FERC* in its Order No. 764 to mandate the partition of each hourly *DAM* period into shorter subperiods.

We begin the chapter by describing the scope and nature of the simulations carried out for the set of representative studies discussed in this chapter. We then proceed to present our results and findings obtained from the case studies. We conclude the chapter with a summary of the key results.

## 4.1 Scope and Nature of the Simulation

In this section, we present a brief description of the test system and provide an overview of the various applications of the proposed methodology presented in Chapter 3 to construct *DAM* and *RTM* offer strategies for frequency service provision. The representative case studies presented serve to illustrate the capabilities of the methodology.

The results we present in the chapter are drawn from the case studies performed using *PJM* and *CAISO* control signal data and price information with the provision of regulation service by a 20 MW *FES* with 5 MWh storage capability. Since the regulation service is procured by the *IGO* on a zonal basis, we do not consider the topology of the grid and assume that all the energy produced by the *FES* can be absorbed by the grid and the grid has the capability to supply the energy charged by the *FES* in the provision of down regulation. This assumption is reasonable given a large system and a limited capacity/capability *FES*. All our studies are performed under the assumption of perfect knowledge of *AGC* signal and are totally deterministic in nature.

The deepening penetration of *VER*s integrated into the grid has driven federal policy, which aims to encourage the further implementation of *VER*s in the most effective way [41]-[42]. Recently *FERC* issued Order No. 764 with the mandate to require *IGO*s to implement intra-hour scheduling changes, i.e., to partition hourly *DAM* periods into smaller subperiods. The shorter *DAM* subperiods introduce certain benefits from the utilization of additional meteorological data for wind and solar generation forecasting due to the higher time resolution. For energy-limited storage resources providing frequency regulation service, the introduction of sub-hourly *DAM* subperiods allows the more cost-effective allocation of the unit's limited energy capability. The simulation approach is constructed by making use of the simulation layer of the framework and has the capability to perform the *FES* economic studies by varying the duration of the *DAM* period. These studies allow the identification of the optimal duration of the *DAM* period for the effective utilization of the *FES* unit in frequency service provision.

The *FES* operator's offer decision into the *DAM*s impacts the *RTM* offers for the entire day *d*. The alternative to the offer of more capacity into the *DAM*s is the additional offer of regulation capacity into the *RTM*s and the reverse. In order to determine the optimal combination of day-ahead and real-time offers, we need to perform an economic assessment of various *DAM*

offer strategies with different durations of the cycle offer pattern $\xi$. Such studies can help to identify the most effective regulation offer strategy into the *DAM*s.

The offer strategies into the hourly *DAM*s and associated *RTM*s formulated in Chapter 3 are made under the "worst-case scenario" assumption for the provision of a single type of regulation service over the entire duration of the period covered by a submitted offer. These strategies provide conservative results under which both up and down regulation can be provided with 100% assurance independent of what the *AGC* signal turns out to be. This very conservative approach does not take into account the inherent uncertain characteristics of the *AGC* signals. The nature of frequency regulation service has been the subject of several studies. The study done by Oak Ridge National Laboratory investigates the mean value of *AGC* requirements over different time durations [1]. It reports that, in most cases, the long-term mean value of the *AGC* curve is in the zero value neighborhood. In light of this finding, we may use a more risky approach in the formulation of the *RTM* capacity offers. In other words, we first scale up the regulation capacity offers, calculated as a result of the proposed approach to determine the real-time offer capacity values:

$$\tilde{v}^{+}_{h,\tau_k} = q\, v^{+}_{h,\tau_k}$$

$$\tilde{v}^{-}_{h,\tau_k} = q\, v^{-}_{h,\tau_k}$$

where $q$ is an augmentation factor > 1. We next examine the economic impacts of such augmented *RTM* capacity offers.

### 4.2 Case Studies Results and Sensitivity Analysis

In this section, we discuss the case study results with the two test data sets from *CAISO* and *PJM*. In order to analyze the differences across the seasons, we disaggregate the *FES* revenues for frequency regulation service provision on a seasonal basis with the months of June, July and August as the summer period, the months of September, October and November as the fall period, the months of December, January and February as the winter period and the months of March, April and May as the spring period. As a reference case for each system we take the existing offer strategy when the *FES* participates only in hourly *DAM*s in which it offers its full capacity to provide up and down regulation services.

Figure 4.1 depicts the average total monthly revenues for capacity in the frequency regulation service provided in each season with different *DAM* offer patterns. Specifically, we change the duration of the cycle offer parameter $\xi$ from 1 to 5. Every monthly payment is represented as a sum of the *DAM* and the *RTM* revenues. We note, that if the *FES* provides service using conventional offer strategy (the reference case), then all payments are calculated based on day-ahead regulation prices. In contrast, if the unit offers service only into *RTM*s ("*RTM* only" case), then the revenues are calculated based on *RTM* prices. For all other cases considered in the study, the total revenues are the sum of the *RTM* and the *DAM* revenues.

From Figure 4.1, we see that for all four seasons the average monthly capacity payment decreases monotonically as the offer cycle $\xi$ increases. The highest increase in monthly capacity revenue is for the offer strategy with $\xi = 1$ in all four seasons. Compared to the base case this strategy provides up to a 4.6% of increase in the monthly revenues. Any increase of $\xi$ obtains no improvements in either the *CAISO* test system or in the *PJM* test system. The "*RTM* only" offer strategy provides revenue growth for the winter months of 2.2%, but in the summer, fall, and spring months, we observe revenue reductions of 2.7%, 0.8%, and 2.4%, respectively.

In Figure 4.2, we plot the monthly *mileage payments* for different *DAM* strategies in the four seasons. We observe increases in the monthly mileage payments under the offer strategy with $\xi = 1$ in the summer and the winter seasons of 4.2 and 6.3%, respectively, with respect to the reference case. On the other hand, for the "*RTM* only" strategy, there is a mileage payment increase for all seasons. The deployment of this strategy provides revenue growth of 4.4, 2.8, 5 and 6.1% for the summer, fall, winter, and spring seasons, respectively, compared with the reference case values. In general, the capacity revenues and mileage payments behave in a similar manner due to the fact that capacity revenues compensate capacity bandwidth of the regulation unit dedicated to provide regulation, i.e., to follow *AGC* signal instructions. As more capacity is provided by the *FES*, the larger the shifts are that the unit needs to perform. Hence, the mileage payment increases is a consequence.

Next, we explore the seasonality effect on the *FES* total monthly revenues. The highest payment for regulation service provision occurs in the summer season. The reason for this is that the summer load is considerably higher than that in the other three seasons. Increases in load cause more volatility in the load-generation balance, consequently the *FES* is instructed to

provide more regulation resulting in additional revenues. This finding holds for both the *CAISO* and the *PJM* test systems.

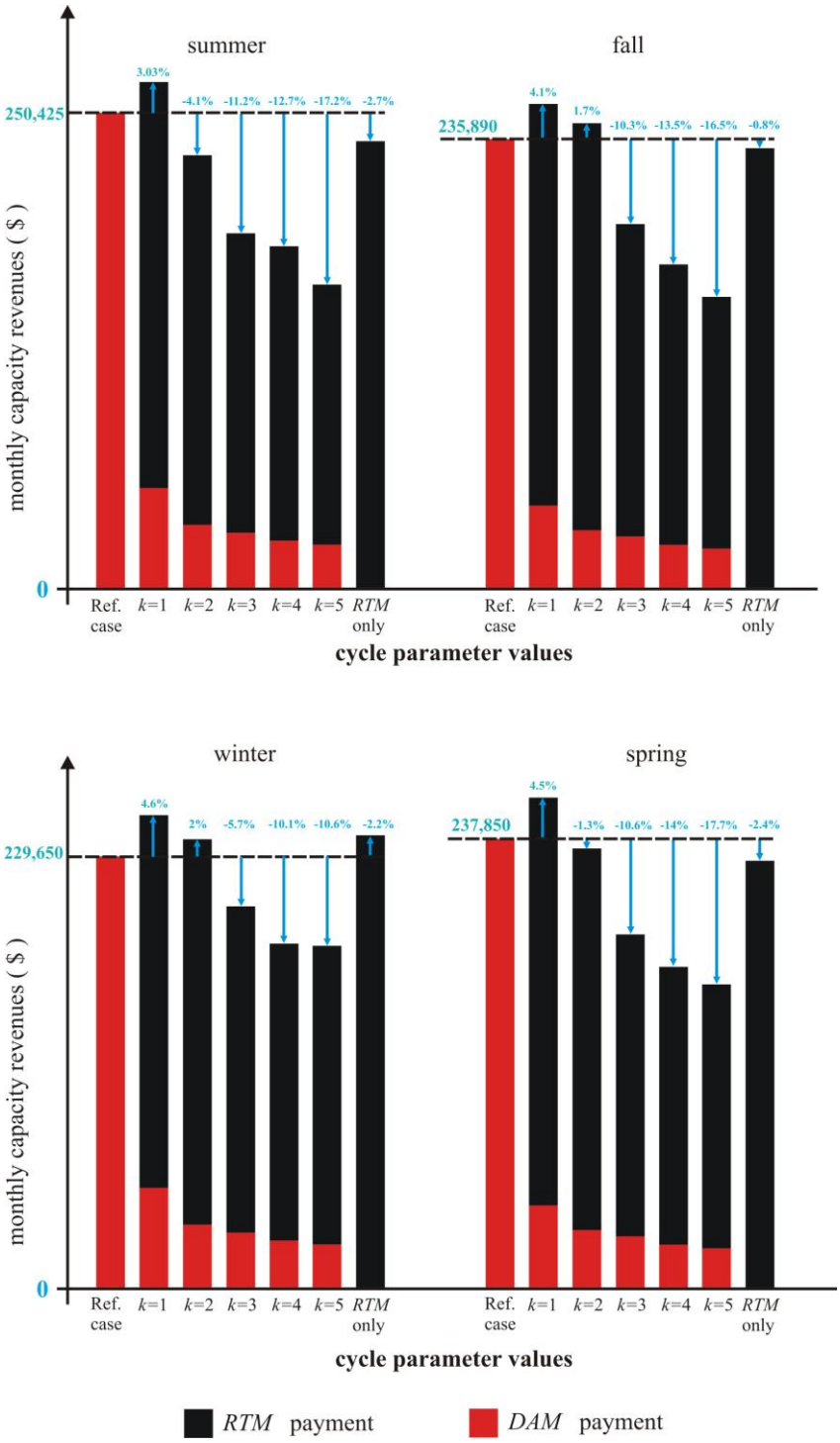


Figure 4.1: The average total monthly revenues for capacity of the delivered frequency regulation service for the *CAISO* test system

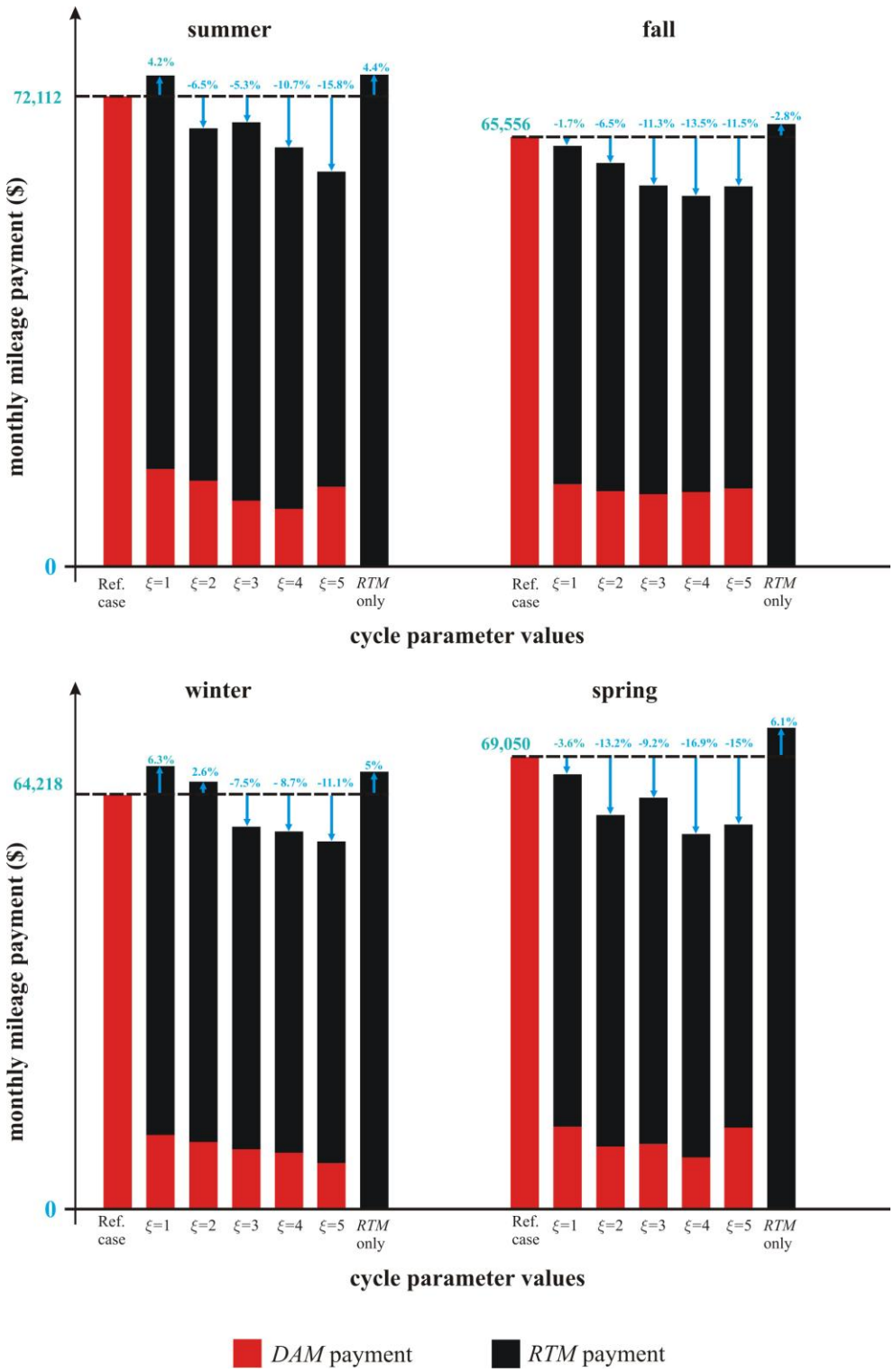


Figure 4.2: The average monthly mileage payments from regulation service in the *DAM*s and the *RTM*s in the *CAISO* test system

In Figure 4.3 we depict the *FES* total monthly revenues for those offer strategies in which we observe an increase in revenues. The total monthly revenues consist of capacity revenues, mileage payments and payments or charges for supplied or consumed energy. In these studies, we do not include the energy payments or charges because their fraction in total payment never exceeds 0.2%. From Figure 4.3 we see that an offer strategy with $\xi = 1$ results in increases in *FES* monthly revenues on 3.3, 3.2, 4.9 and 2.7% for the summer, fall, winter, and spring seasons, respectively, with reference to the conventional approach. Moreover, for the winter season, we observe the increase in the *FES* revenues of 2.1 and 2.8% for the *DAM* strategy with $\xi = 2$ and "*RTM* only" offer strategies, respectively, with reference to the conventional case.

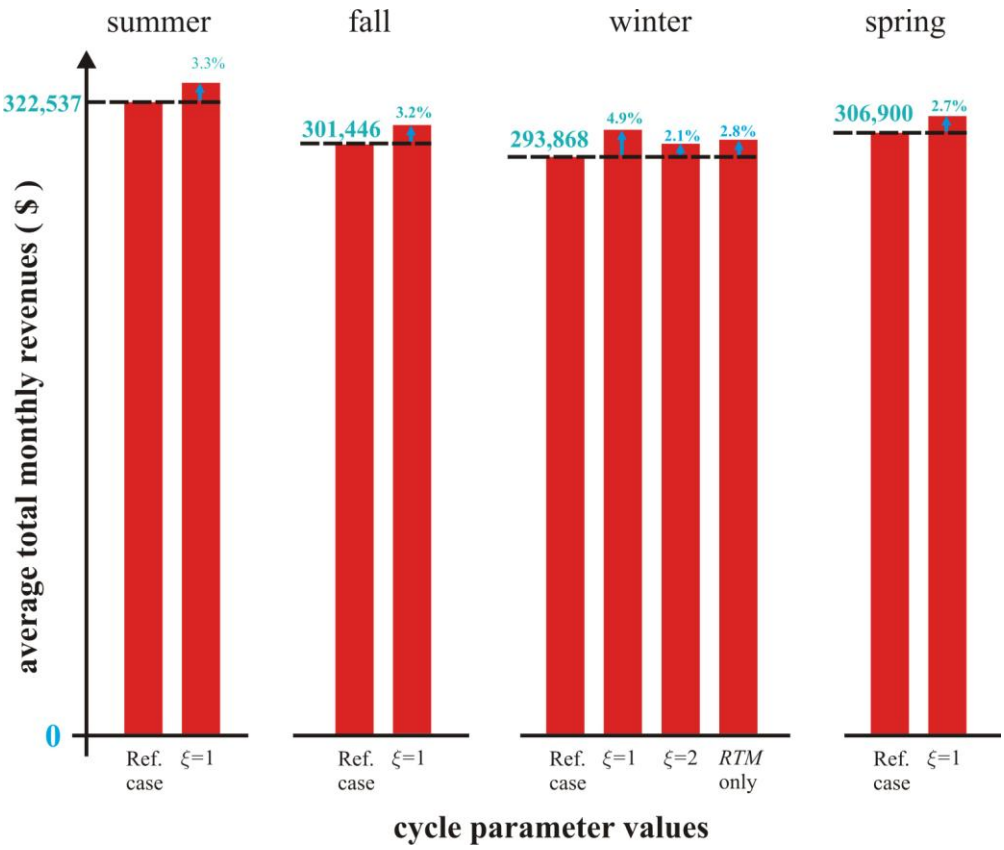


Figure 4.3: The monthly total revenues for regulation service in the *CAISO* test system

In Section 4.1, we discussed the *FERC* Order No. 764 obligation on the *IGO*s to partition the hourly *DAM* periods into shorter intervals. This order impacts *FES* regulation service

providers with benefits since with the shorter duration subperiods, the provider manages its stored energy more effectively. However, there is the lingering question as to the most beneficial duration of the *DAM* period for the *FES* frequency regulation service provision. In order to answer this question we performed an extensive sensitivity study on the *DAM* period duration. To illustrate the impact of a *DAM* period reduction, we depict in Figures 4.4–4.6 the total monthly regulation service provider revenues with *DAM* period durations of 15, 20, and 30 minutes under different service provision cycles $\xi$. The conventional offer strategy serves as the reference for the analysis of simulation results. For a 15-minutes *DAM* period, the peak monthly revenues are obtained with the cycle $\xi = 3$. Smaller $\xi$ values result in lower revenues because of less effective *FES* stored energy utilization. On the other hand, for $\xi > 3$ the limited *FES* storage capability limits the unit ability to offer more capacity on regulation into the *DAM*s. Therefore, the monthly revenues decrease. For 20- and 30-minute *DAM* periods, the monthly revenues are higher for $\xi = 1$, as illustrated in Figures 4.5 and 4.6. These results are commensurate with those obtained for case studies with hourly periods, but since we have the finer granularity for regulation provided in the *DAM*s, the monthly revenues increase above the reference case levels obtained with one-hour *DAM* periods.

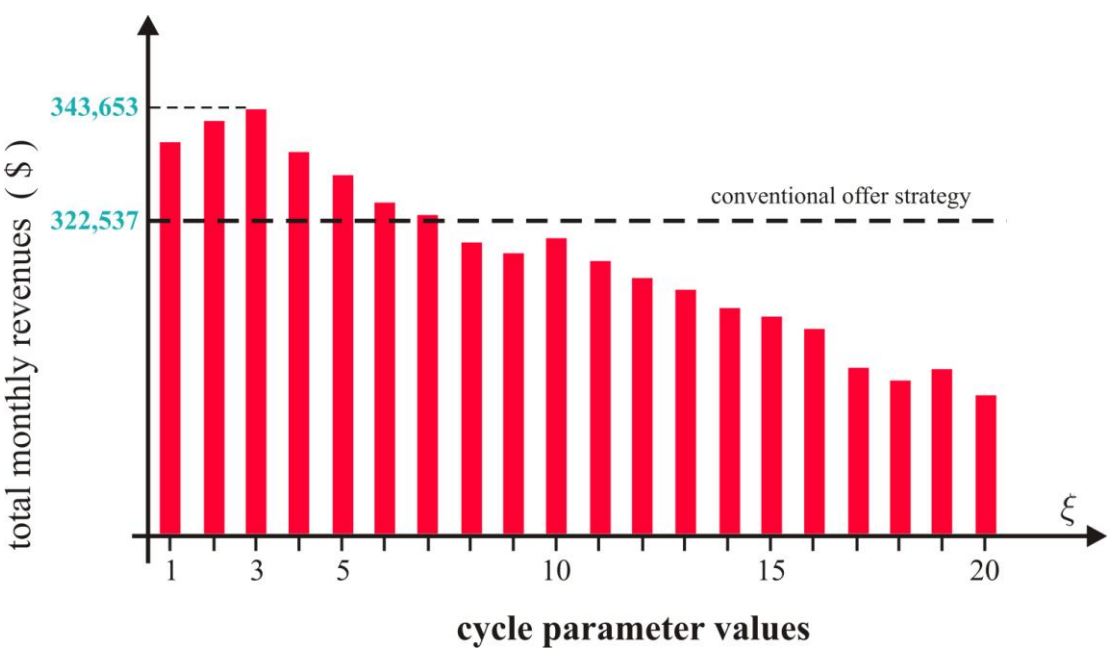


Figure 4.4: Total monthly *FES* revenues under 15-minute *DAM* periods

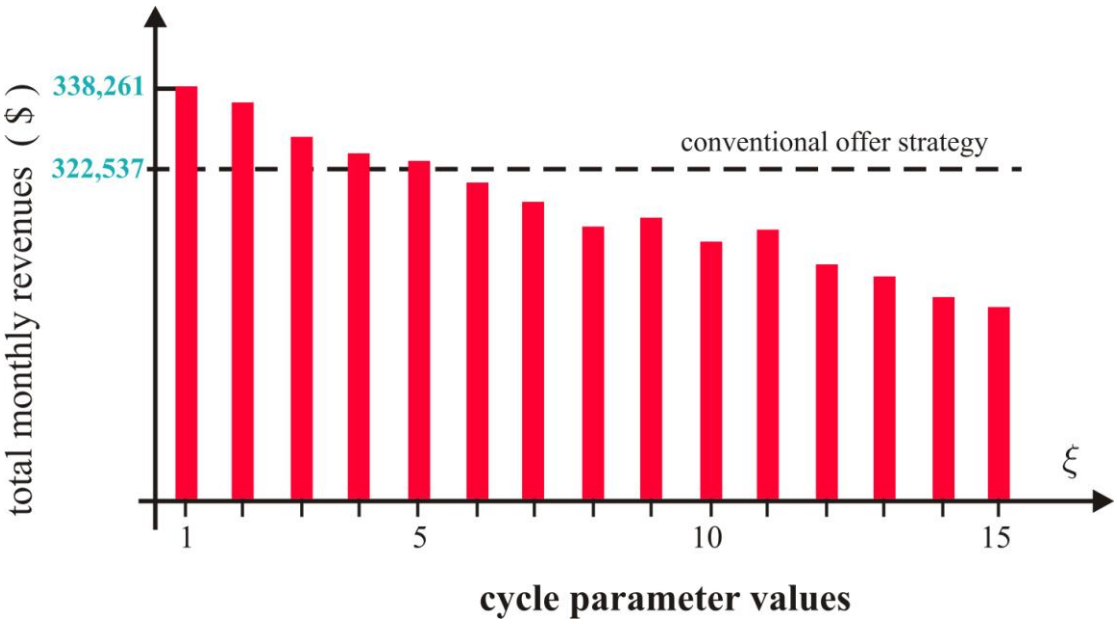


Figure 4.5: Total monthly *FES* revenues under 20-minute *DAM* periods

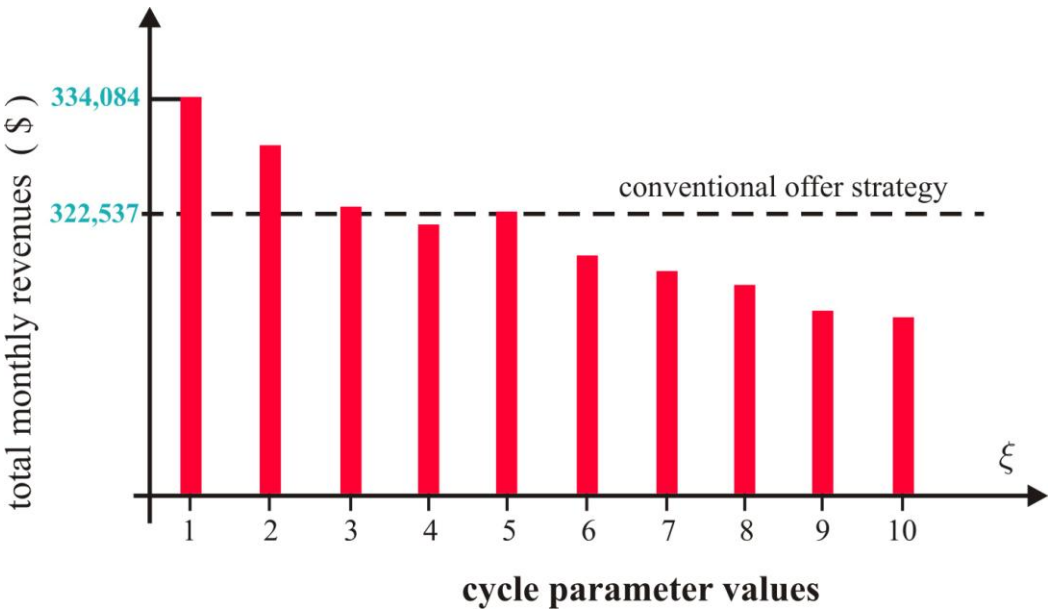


Figure 4.6: Total monthly *FES* revenues under 30-minute *DAM* periods

From this discussion we conclude that the *FES* can benefit from the reduced duration *DAM* period. The *DAM* period duration of 15 minutes combined with appropriate *DAM* offer strategy

$\xi = 3$ provides the largest increase in monthly revenues. For the 20- and 30-minute *DAM* periods, the revenue increases are smaller, but are still above those in the reference case.

We next investigate the impacts on *FES* monthly revenues of the deployment of risk-taking offer strategies into the *RTM*s. In our studies we parametrized the augmentation factor *q* to calculate *FES* total revenues for a given value of $\xi$. Figure 4.7 depicts the plot of the *FES* total monthly revenues for $\xi = 1$ and $\xi = 2$. The plots for $\xi = 3, 4$ and $5$ are not of interest, since the total monthly revenues are below those in the reference case. From Figure 4.7 we see that for $\xi = 1$ with $100\% \leq q \leq 160\%$, as $q$ increases the monthly total revenues increase. This means that the benefits from the additional capacity of the offer exceed the revenue losses from the inability to respond to *AGC* signals due to hitting a storage capability limit. If we increase *q* above 160% we obtain no revenue increases because of the reduction in the number of $\sigma$ intervals when the *FES* is responsive to *AGC* signals. Such a reduction causes the decrease in capacity revenues and mileage payments, and, therefore, in the total revenues.

We see that the choice of *q* involves a trade-off: *q* needs to be large enough to have an impact on capacity revenues and mileage payments, but also needs to be sufficiently small to avoid hitting a storage capability limit during regulation service provision. We obtain a similar plot for $\xi = 2$ with peak monthly revenues with $q = 170\%$.

In order to obtain a better representation of the relationship between *q* and monthly revenues, we display the *q* sensitivity for $150\% \leq q \leq 170\%$ under $\xi = 1$ in Figure 4.8. We see that the peak monthly revenues of $353,403 corresponding to the *RTM* capacity offer augmentation by 63%. In this case, we have an increase in monthly revenues of $30,867, which is a meaningful amount for a *FES* service provider.

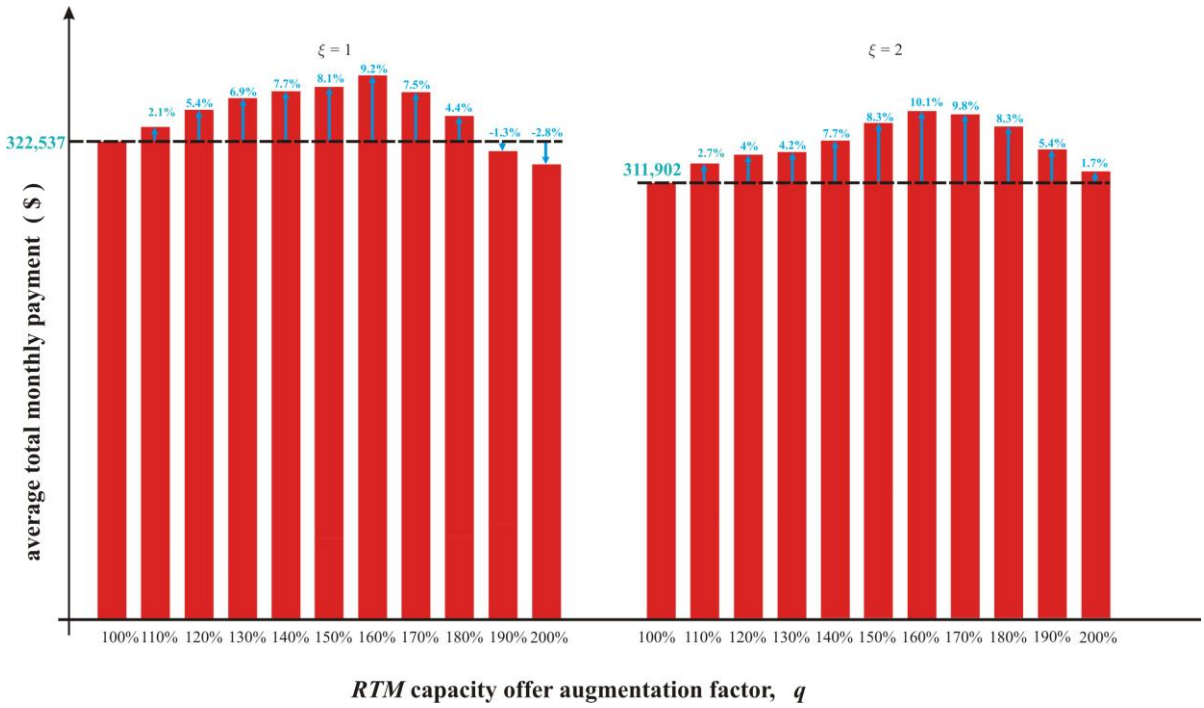


Figure 4.7: Total *FES* revenues for *RTM* capacity offer augmentation over the $110\% \leq q \leq 200\%$ with $\xi = 1$ and 2

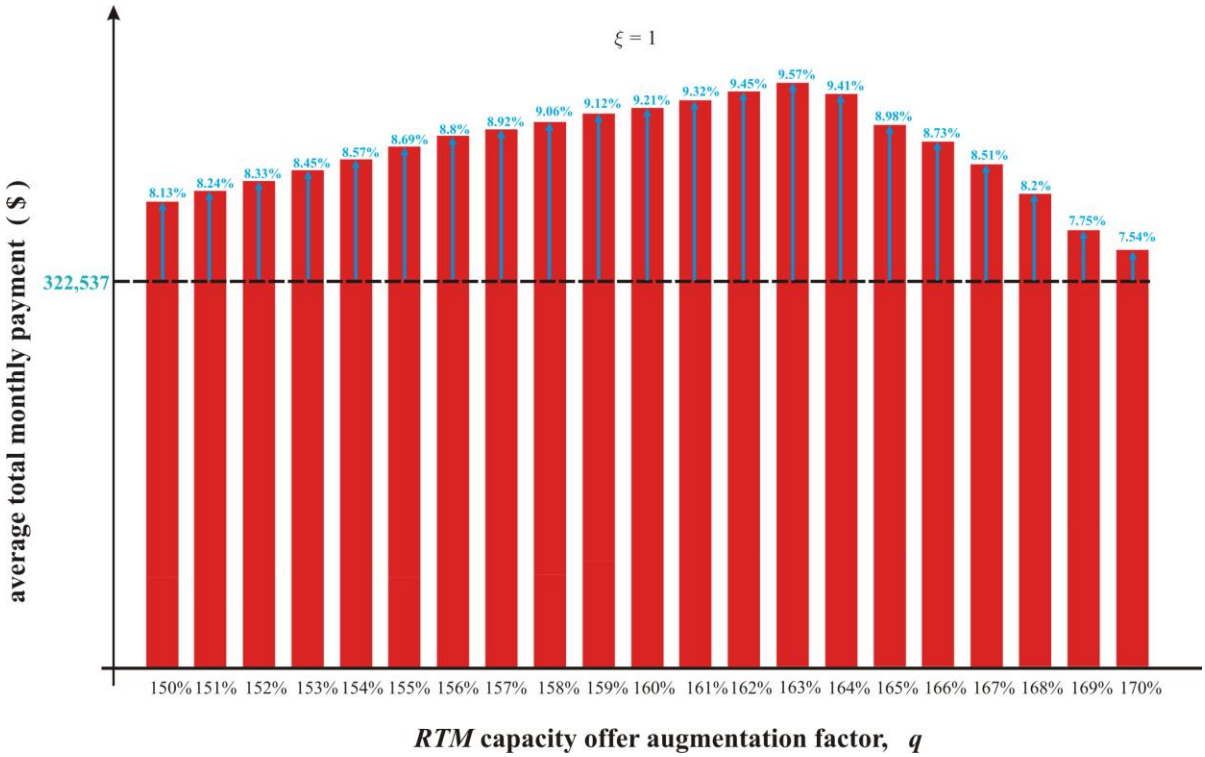


Figure 4.8: Total *FES* revenues for *RTM* capacity offer augmentation over the $150\% \leq q \leq 170\%$ with $\xi = 1$

### 4.3 Summary

In this chapter we demonstrated the ability of the proposed formulation for the offer strategies into *DAM*s and their associated *RTM*s through representative case studies using the actual 2011 year *AGC* signals and the price data from two large systems – the *CAISO* and the *PJM*. Studies show that the offer strategies formulated for the *FES* participation in the *DAM*s and the *RTM*s result in the provision of guaranteed service fully responsive with the *AGC* signals sent by the *IGO*. We also presented the studies to investigate the impacts of changing the duration of the cycle offer pattern parameter $\xi$ for the *DAM*s so as to bring about the most effective utilization of the *FES* unit. With a 20 MW *FES* with 5 MWh storage capability in the 2011 *CAISO* data case, such utilization results from participation in every other hourly *DAM* – i.e., a cycle of one hour participation followed by one hour of non-participation – to have 12 consecutive such cycles each day. The simulation study results for this specific case indicate that this cycle increases the *FES* annual revenues by 3.3% over those with the current *FES* offer strategy at full capacity for every hourly *DAM*. We also studied the impacts of the deployment of risk-taking offer strategies into the *RTM*s. We find that such offer strategies into the *RTM*s result in increases in *FES* monthly revenues. Specifically, the increase of the *RTM* capacity in the up and down regulation service offers by 63% increases the monthly revenue by nearly 10% over the risk-free conservative strategy. A very insightful application of the proposed approach is to the analysis of policy issue impacts. Our studies indicate that the mandate of the *FERC* Order No. 764 to introduce shorter *DAM* subperiods result in improved utilization of storage and in increases in revenues for the frequency regulation service provision.

# CHAPTER 5

# CONCLUSIONS

In Section 5.1, we provide a brief synopsis of the work presented in this thesis. In Section 5.2, we detail directions for future work for the utilization of *FES* resources in frequency regulation service provision.

## 5.1 Summary

In this thesis we have developed a comprehensive approach to effectively utilize *FES* resources to provide guaranteed *AGC* service to the grid. The approach makes detailed use of the analytic framework we have developed for both analysis and simulation purposes. The framework incorporates the regulatory, financial and physical considerations in frequency regulation service provision by a *FES* unit and constructs the analytical basis for the formulation of offers into the two sets of markets – the *DAM*s and the *RTM*s. The framework has a three-layer structure – a layer for offer formulation into the hourly *DAM*s, another layer for additional offer formulation into the *RTM*s and a simulation layer of *FES* operations in response to the *AGC* signals sent by the system operator into whose system the *FES* is integrated. The analytic basis in the framework allows the determination of the appropriate constraints for use in the formulation of the offers for each set of markets. This basis incorporates the modeling of the *FES* unit

developed to appropriately represent its salient physical characteristics with different levels of granularity in the three layers. In addition, the representations of the market rules are embedded in each layer. The models in the *DAM* and the *RTM* layers are able to provide the respective boundary limits under worst-case scenario of one type regulation service over the entire duration of the period covered by a submitted offer. As a result, the offer is formulated with the full assurance that the frequency regulation service can be provided over the entire period associated with the offer so as to satisfy all the physical and the regulatory constraints.

The application of the framework to the formulation of offer strategies makes use of robust optimization concepts in the solution of the optimization problem to determine the amount of the up and down regulation to offer in each market for each period/subperiod. These solutions provide conservative results under which both up and down regulation can be provided with 100% guarantee independent of what the *AGC* signal turns out to be and taking into account the most up-to-date information on the unit status at the time the offer is submitted. To obtain these results, we take full advantage of the distinct considerations in the hourly *DAM* and in its associated *RTM*s. The offers for each market are made at different times and we use participation in the *RTM* to adaptively correct the accepted offer into its associated *DAM* by detailed use of the updated information on the *FES* stored energy level. We also investigated the modification of the conservative solutions to construct more risky *RTM* offers and evaluate their performance over a range of values of the capacities for regulation up and down service provision.

We have demonstrated the capability of the developed approach and quantified the improved performance over existing techniques through various case studies using the historical *AGC* signal and price data from two large systems – the *CAISO* and the *PJM*. The representative studies presented in this thesis show that the offer strategies formulated for the *FES* participation

into the *DAM*s and the *RTM*s provide guaranteed service fully responsive to the *IGO* sent *AGC* signals. The specific studies that investigated the impacts of changing the duration of the cyclic offer pattern in the *DAM*s to bring about the best utilization of the *FES* unit provide important insights into the cycle choice. For the 2011 *CAISO* data case, the best utilization results from participation in every other hour's *DAM* – i.e., a cycle of one hour participation followed by one hour of non-participation – to have 12 consecutive such cycles per day. Indeed, the results indicate that this cycle increases the *FES* annual revenues by 3.3% over those with the current *FES* offer strategy. We also studied the impacts of the deployment of risky offer strategies into the *RTM*s. We find that such offer strategies in the *RTM*s results in increased *FES* monthly revenues.

A very insightful application of the proposed approach is to the analysis of policy issues. We illustrate such an application through an analysis of the changes promulgated by *FERC* in its Order No. 764 to mandate the partitioning of each hourly *DAM* period into four 15-minute subperiods. Our studies indicate that the shorter subperiods result in improved utilization of the storage capability and in increases in revenues for the frequency regulation service over those for the hourly periods. These representative results clearly indicate that the proposed approach generates offer strategies that result in the better utilization of the *FES* to provide guaranteed frequency regulation service.

## 5.2 Directions for Future Work

The thesis reported constitutes a good starting point for the future study of additional issues related to frequency regulation provision by storage technologies. The ongoing advancements in

flywheel technology motivate the parametric study of the sensitivity of the regulation service provision with respect to improvements obtainable from capacity and storage capability increases of *FES* units. Such studies can also shed light on the willingness to pay for such improvements by the *FES* owners.

In light of recent experiences in the deployment of storage devices for frequency regulation service provision an interesting extension of the work is the consideration of optimal deployment of aggregations of multiple *FES* units with both uniform and non-uniform characteristics. In considering the aggregation of multiple *FES* units, the important question that is raised, is whether it makes sense to cluster the *FES* units into various subgroups so as to allow their more effective utilization for frequency regulation service provision. Such a question can be answered as part of a broader problem concerning the effective utilization of a fleet of different storage technologies, say, hydro, *FES* and large-scale batteries. The formulation of an answer to this question requires the extension of the framework to include the representation of all the technologies of interest.

Another issue that requires future work is the deployment of the extended framework to formulate the appropriate incentives to stimulate the energy storage suppliers to provide guaranteed frequency regulation service. Such an investigation needs to formulate appropriate payments to the storage resources so as to veer them away from the submission of risky offers to provide guaranteed service.

# APPENDIX A

# NOTATION USED IN THE THESIS

For the *DAM* layer we adapt the convention that the hour *h* starts at (*h*-1:00:00)$^+$ and ends at *h*:00:00 and so the hour excludes the point (*h*-1:00:00) and includes *h*:00:00. Hence, the hour *h* is represented by semi-open time interval, as shown in Figure A.1.

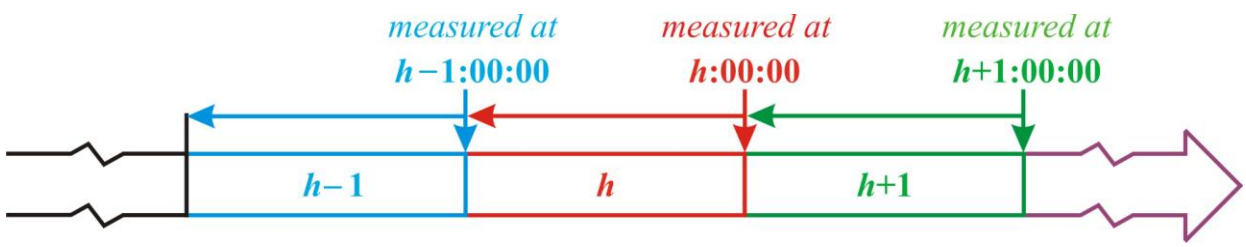


Figure A.1: Hourly intervals for the *DAM*

Each *DAM* has an hour as the smallest indecomposable unit of time and no phenomena of shorter duration may be represented in a *DAM*. We represent the system by its snapshot whose values are assumed to hold for the entire hour. We define the set of *H* hours $\mathcal{H} = \{1, 2, \ldots, H\}$ to denote the collection of the hours for which the *DAM*s are cleared and the outcomes are determined.

Under the selection of an hour as a smallest indecomposable unit of time, we are unable to represent any phenomenon of any duration under an hour. Therefore, we have adopted the following protocol: all values on *DAM* are established at the end of the hour and they are assumed to hold over the entire hour (Figure A.1). For example, *DAM* capacity award $\kappa_h^-$ ($\kappa_h^+$)

for regulation down (up) is constant for the entire hour *h*, energy charge $\varepsilon_h$ is measured at the single point in time *h* :00:00 and assumed to hold over the entire hour *h*.

The similar protocol is applicable for the *RTM* layer, when we consider a subperiod $\tau_k$ as the smallest indecomposable unit of time. The variables associated with each *RTM* are assumed to be constant for the entire subperiod $\tau_k$ and subscript $(h, \tau_k)$ of a variable represents the *RTM* variables. We define the subset of *K* equal duration subperiods $\mathcal{T}_h = \left\{\tau_1, \tau_2, \ldots, \tau_K\right\}$ in hour *h*, one for each *RTM* with duration $\frac{60}{K}$ minutes in that hour. We adopt the protocol that the subperiod $\tau_k$ of hour *h* starts at $(h-1:\frac{60(k-1)}{K}:00)^+$ and so the subperiod $\tau_k$ excludes the point $(h-1:\frac{60(k-1)}{K}:00)$ and includes $(h-1:\frac{60k}{K}:00)$. Hence, each subperiod $\tau_k$, $k = 1, 2, \ldots, K$, is represented by the semi-open time interval that covers the range from $(h-1:\frac{60(k-1)}{K}:00)^+$ to $(h-1:\frac{60k}{K}:00)$, as we indicate for the semi-open intervals in Figure A.2.

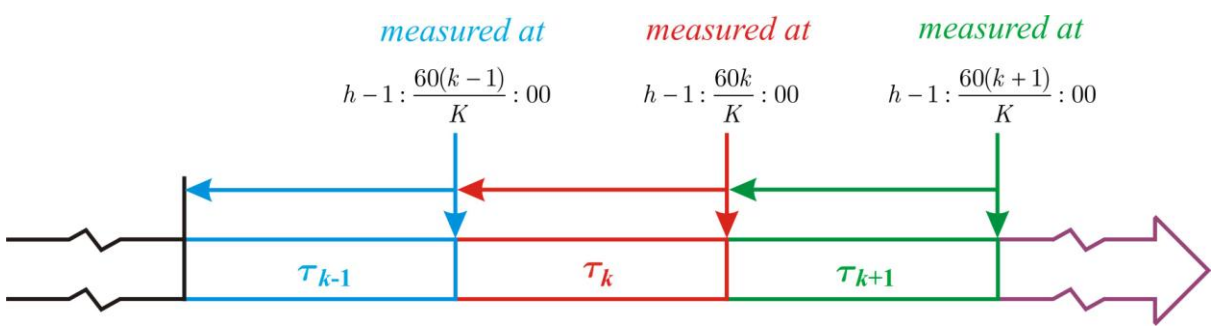


Figure A.2: The subperiods $\tau_k$ for each *RTM* are semi-open intervals

All values on *RTM* are established at the end of the subperiod $\tau_k$ and they are assumed to hold over the entire subperiod $\tau_k$. Thus, energy charge $s_{h,\tau_k}$ is measured at the single point in

time ($h-1:\frac{60k}{K}:00$) and assumed to hold over the entire subperiod $\tau_k$ of hour *h*, *RTM* capacity award $\nu^{+}_{h,\tau_k}$ ($\nu^{-}_{h,\tau_k}$) for regulation up (down) is constant for the entire subperiod $\tau_k$ of hour *h*.

We next examine the *AGC* physical operations layer to effectively represent the *AGC* intervals. The values during real-time operation under *AGC* are assumed to be constant for the entire interval $\sigma_n$. We use the variable $\sigma_n$ in square brackets to denote the variables relating to physical operation under *AGC*. We define a subset of *N* equal duration intervals $\mathcal{I}_{h,\tau_k}=\{\sigma_1,\sigma_2,\ldots,\sigma_N\}$ in subperiod $\tau_k$ of hour *h*, one for each *AGC* signal with duration $\frac{3600}{KN}$ seconds.

We adopt the protocol that the interval $\sigma_n$ of subperiod $\tau_k$ of hour *h* starts at ($h-1:\frac{60(k-1)}{K}:\frac{3600(n-1)}{KN}$)$^{+}$ and ends at ($h-1:\frac{60(k-1)}{K}:\frac{3600n}{KN}$) and so the interval $\sigma_n$ excludes the point ($h-1:\frac{60(k-1)}{K}:\frac{3600(n-1)}{KN}$) and includes ($h-1:\frac{60(k-1)}{K}:\frac{3600n}{KN}$). Hence, each interval $\sigma_n$, $n=1,2,\ldots,N$, is represented by the semi-open time interval that covers the range from ($h-1:\frac{60(k-1)}{K}:\frac{3600(n-1)}{KN}$)$^{+}$ to ($h-1:\frac{60(k-1)}{K}:\frac{3600n}{KN}$).

Similarly to *RTM* and *DAM* layers, all values relating to physical operations under *AGC* are established at the end of the interval $\sigma_n$ and they are assumed to hold over the entire interval $\sigma_n$. For example, capacity output $c_{h,\tau_k}[\sigma_n]$ is assumed to be constant for the entire interval $\sigma_n$, energy charge $\varepsilon_{h,\tau_k}[\sigma_n]$ is measured at the single point in time ($h-1:\frac{60(k-1)}{K}:\frac{3600n}{KN}$) and assumed to hold over the entire interval $\sigma_n$. Figure A.3 depicts the semi-open intervals $\sigma_n$ of physical operations under *AGC*.

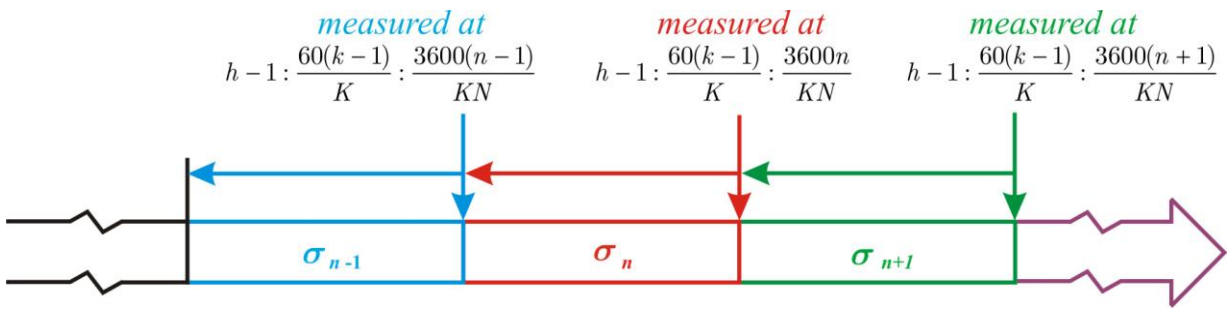


Figure A.3: The intervals $\sigma_n$ of physical operations under *AGC*

Figure A.4 represents the time segments of *DAM*, *RTM* and physical operations under *AGC* layers.

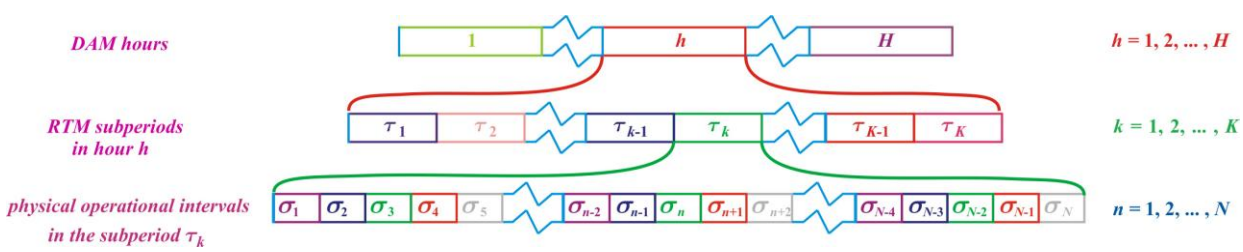


Figure A.4: Time frame for the *AGC* service in the market environment

Key aspects include the following:

- The elements of each offer have the $\hat{}$ notation
- All *regulation up-related* variables/parameters have the superscript "+"
- All *regulation down-related* variables/parameters have the superscript "–"
- We define $\dagger = \begin{cases} + \text{ for regulation up service} \\ - \text{ for regulation down service} \end{cases}$

*RTM*-related notation (units):

$\nu^{\dagger}_{h,\tau_k}$ : *RTM* regulation capacity for subperiod $\tau_k$ in hour $h$ (MW)

$\chi^{\dagger}_{h,\tau_k}$ : *RTM* regulation capacity price for the subperiod $\tau_k$ in hour $h$ ($/MW/h)

$\varphi_{h,\tau_k}$ : *RTM* regulation mileage price for the subperiod $\tau_k$ in hour *h* ($/MW)

$\underline{\underline{\alpha}}_{h,\tau_k}$ : a pre-specified lower bound of *s.o.c.* at the end of subperiod $\tau_k$ in hour *h* (MWh)

$\overline{\overline{\alpha}}_{h,\tau_k}$ : a pre-specified upper bound of *s.o.c.* at the end of subperiod $\tau_k$ in hour *h* (MWh)

$s_{h,\tau_k}$ : value of *s.o.c.* at the end of subperiod $\tau_k$ in hour *h* (MWh)

*DAM*-related notation:

$\kappa_h^{\dagger}$ : *DAM* regulation capacity in hour *h* (MW)

$\rho_h^{\dagger}$ : *DAM* regulation capacity price in hour *h* ($/MW/h)

$\mu_h$ : *DAM* regulation mileage price in hour *h* ($/MW)

$\underline{\underline{e}}_h$ : a pre-specified lower bound of state of charge (*s.o.c.*) at the end of hour *h* (MWh)

$\overline{\overline{e}}_h$ : a pre-specified upper bound of *s.o.c.* at the end of hour *h* (MWh)

$\varepsilon_h$ : value of *s.o.c.* at the end of hour *h* (MWh)

Physical operations under the *AGC*-related notation:

$p^{M,\dagger}$ : regulation resource maximum capacity output (MW)

$p^{m,\dagger}$ : regulation minimum capacity offer (MW)

$c_{h,\tau_k}[\sigma_n]$ : regulation resource output in interval $\sigma_n$ of subperiod $\tau_k$ of hour *h* (MW)

$E^M$ : energy charge upper physical limit (MWh)

$E^m$ : energy charge lower physical limit (MWh)

$\varepsilon_{h,\tau_k}[\sigma_n]$ : value of energy charge level at the end of interval $\sigma_n$ of subperiod $\tau_k$ in hour *h*

$r^M$ : maximal ramping rate (MW/min)

# APPENDIX B

# THE PROCEDURE TO CALCULATE THE PAYMENT FOR *FES* REGULATION SERVICE PROVISION

We devote this appendix to describe the procedure the *IGO* is mandated to implement in order to calculate the regulation unit's revenues from participating on regulation *DAM*s and *RTM*s.

Compensation to unit providing frequency regulation service is based on regulation clearing prices, the unit's actual performance in response to *AGC* signal and contractual obligations for frequency regulation provision on the *DAM*s and *RTM*s.

The total payment includes following components:

(i) Cleared capacity payments for the *DAM*s and *RTM*s

(ii) Mileage payments for the *DAM*s and *RTM*s

(iii) Payments or charges for the net energy the unit injects into or withdrawals from the system while following the *AGC* signal

*FERC* Order No. 755 establishes the following procedure to calculate every component of compensation:

1. The payment for capacity of the delivered frequency regulation service is compensation to the *FES* for the capacity range which the unit made available to operate under *AGC*. This payment depends on the number of *AGC* intervals, when the unit was responsive to the *AGC* signal. Note, that *FES* is not able to respond to the *AGC* signal if the unit hits its upper or lower stored energy limit. The total payment for capacity of the delivered frequency regulation service consists of two parts. The first one is based on the *DAM* clearing price, and the

second is based on the *RTM* clearing price, as illustrated in Figure B.1. Let us first consider the *RTM* component.

At any subperiod $\tau_k$, we need to know how many *AGC* intervals the *FES* was not able to respond to *AGC* signal due to the low charge level. We define an indicator function $i^{+}_{h,\tau_k}[\sigma_n]$ by

$$i^{+}_{h,\tau_k}[\sigma_n] = \begin{cases} 1 & \text{if} \quad \varepsilon_{h,\tau_k}[\sigma_n] = E^{m} \\ 0 & \text{otherwise} \end{cases}$$

Similarly, we define a function $i^{-}_{h,\tau_k}[\sigma_n]$ to indicate the *AGC* intervals when *FES* was not able to respond to *AGC* signal due to hitting the upper level of stored energy:

$$i^{-}_{h,\tau_k}[\sigma_n] = \begin{cases} 1 & \text{if} \quad \varepsilon_{h,\tau_k}[\sigma_n] = E^{M} \\ 0 & \text{otherwise} \end{cases}$$

Then, the payment $\eta_h$ for capacity of the delivered frequency regulation service for *KRTM*s in hour *h* can be defined as:

$$\eta_h = \sum_{k=1}^{K} \left( \nu^{+}_{h,\tau_k} \; \chi^{+}_{h,\tau_k} \left[ 1 - \frac{\sum_{n=1}^{N} i^{+}_{h,\tau_k}[\sigma_n]}{N} \right] + \nu^{-}_{h,\tau_k} \; \chi^{-}_{h,\tau_k} \left[ 1 - \frac{\sum_{n=1}^{N} i^{-}_{h,\tau_k}[\sigma_n]}{N} \right] \right)$$

Similarly, the payment $\pi_h$ for capacity of the delivered frequency regulation service for *DAM* obligations fulfillment in hour *h* can be defined as:

$$\pi_h = \kappa^{+}_h \; \rho^{+}_h \left[ 1 - \frac{\sum_{k=1}^{K} \sum_{n=1}^{N} i^{+}_{h,\tau_k}[\sigma_n]}{NK} \right] + \kappa^{-}_h \; \rho^{-}_h \left[ 1 - \frac{\sum_{k=1}^{K} \sum_{n=1}^{N} i^{-}_{h,\tau_k}[\sigma_n]}{NK} \right]$$

As a result, the total payment for capacity of the delivered frequency regulation service for a day *d* includes the payments which come from the contractual obligation to provide regulation service on hourly *DAM*s and associated *RTM*s and is given as

$$\gamma = \sum_{h=1}^{H} \left( \pi_h + \eta_h \right)$$

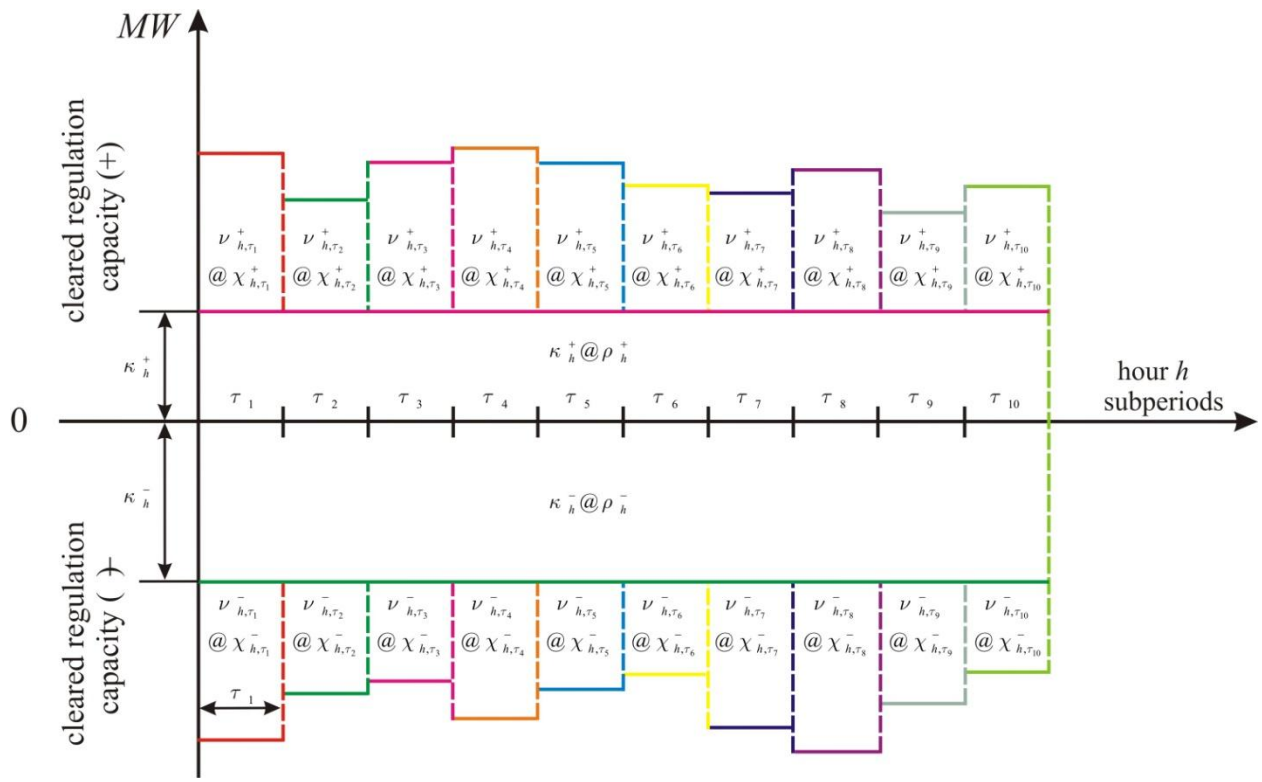


Figure B.1: Capacity payment based on the *RTM* and the *DAM* clearing outcomes

2. Under the *FERC* Order No. 755, every regulation unit must be compensated for the actual change in output between two consecutive *AGC* signal responses. The *FERC* Order No. 755 also refers to this component as a mileage payment. Since *FERC* does not provide exact guidance on how to calculate mileage payments, every *IGO* has established its own mileage compensation scheme. Reference [39] provides the detailed analysis of the *IGO*s policies and in this thesis we use the more general approach presented in [43].

The mileage payment is based on absolute change of the unit's output $c_{h,\tau_k}[\sigma_n]$ between two consecutive $\sigma$ intervals as depicted in Figure B.2. In other words, this payment compensates the regulation unit for actual capacity movements in response to the *AGC* signal instruction. So, if the unit participates only on *DAM* or *RTM*, then the mileage compensation is paid at the *DAM* or *RTM* clearing price. For general cases, when the unit is cleared both on *DAM*

and *RTM* for the frequency regulation provision, mileage payment consists of two components paid at the *DAM* and *RTM* clearing prices, respectively. Specifically, all the capacity movements which are between *DAM* up $\kappa_h^+$ and down $\kappa_h^-$ cleared capacities are compensated based on *DAM* clearing price $\mu_h$:

$$\vartheta_h = \mu_h \sum_{k=1}^{K}\sum_{n=1}^{N}\left(\begin{array}{l} \left|max\ \left\{0,\ \ \kappa_h^+ - c_{h,\tau_k}[\sigma_n]\right\} - max\ \ \left\{0,\ \ \kappa_h^+ - c_{h,\tau_k}[\sigma_{n+1}]\right\}\right| - \\ -\left|max\ \left\{0,\ -\kappa_h^- - c_{h,\tau_k}[\sigma_n]\right\} - max\ \ \left\{0,\ -\kappa_h^- - c_{h,\tau_k}[\sigma_{n+1}]\right\}\right| \end{array}\right)$$

Additionally, all movements above $\kappa_h^+$ and below $\kappa_h^-$ are considered as *RTM* mileage and are paid at the *RTM* mileage clearing price $\varphi_{h,\tau_k}$:

$$\phi_h = \sum_{k=1}^{K}\varphi_{h,\tau_k}\sum_{n=1}^{N}\left(\left|c_{h,\tau_k}[\sigma_n] - c_{h,\tau_k}[\sigma_{n+1}]\right| - \left(\begin{array}{l} \left|\max\left\{0,\ \kappa_h^+ - c_{h,\tau_k}[\sigma_n]\right\} - \max\left\{0,\ \kappa_h^+ - c_{h,\tau_k}[\sigma_{n+1}]\right\}\right| - \\ -\left|\max\left\{0,\ -\kappa_h^- - c_{h,\tau_k}[\sigma_n]\right\} - \max\left\{0,\ -\kappa_h^- - c_{h,\tau_k}[\sigma_{n+1}]\right\}\right| \end{array}\right)\right)$$

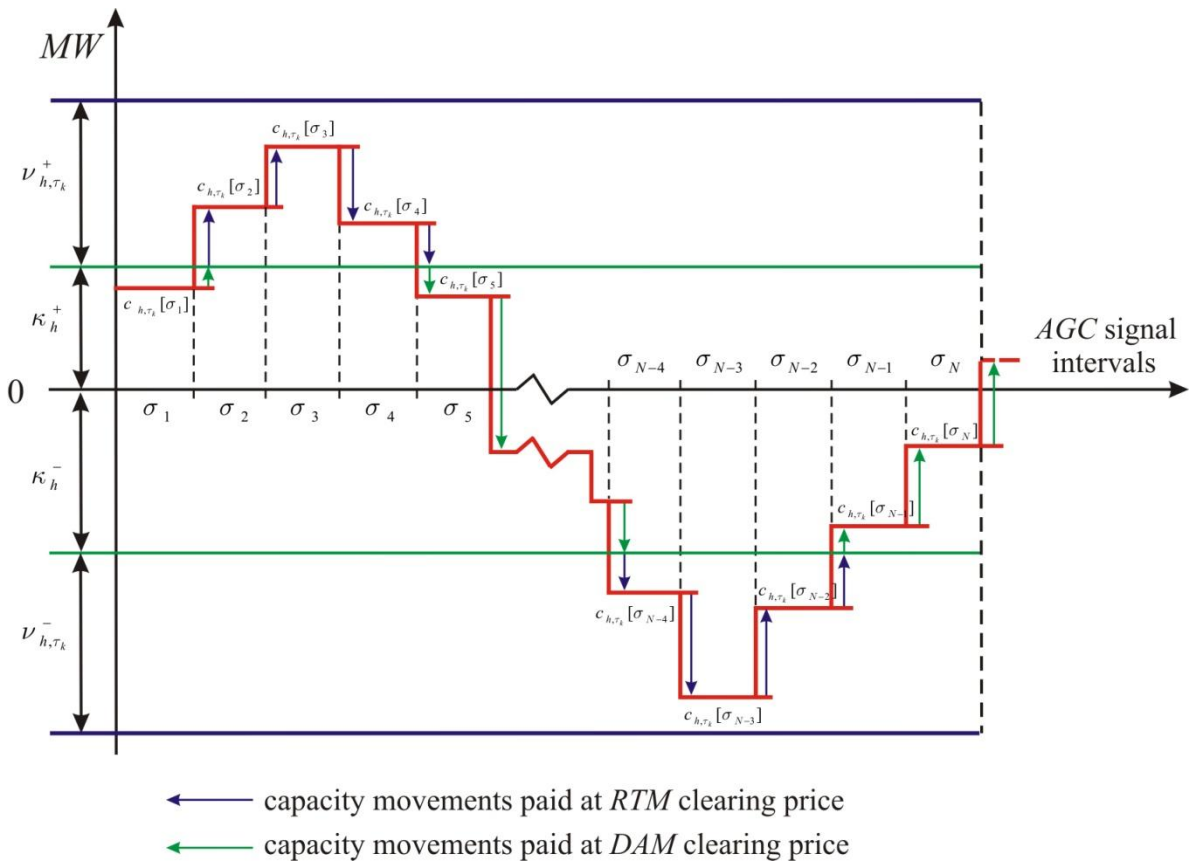


Figure B.2: Mileage payment calculation

The total mileage payment for a day *d* is presented as follows:

$$\psi = \sum_{h=1}^{H} \left( \vartheta_h + \phi_h \right)$$

3. In Order No. 755 the *FERC* mandated all *IGO*s to compensate or charge resources providing frequency regulation service for the net energy injected or withdrawn while following *AGC* signal commands. It is important to note that *IGO*s policies have different energy compensation schemes. For example, *CAISO* and *PJM* pay or charge the net energy at the real-time *LMP* only. As a justification of their approach, they claim that their revenues come mostly from payments for regulation provision, but not from energy arbitrage. In this thesis we have adopted a more general compensation scheme. In particular, the *FES* is paid or charged for the net energy injected or withdrawn at the hourly *LMP* if the resource's output is between *DAM* up $\kappa_h^+$ and down $\kappa_h^-$ cleared capacities. On the other hand, if the resource's output is above $\kappa_h^+$ or below $\kappa_h^-$, then the energy generated or consumed is considered as an *RTM* transaction and is compensated or charged at the real-time *LMP* as designated by right-directed hatching under the *AGC* signal on Figure B.3.

In order to distinguish between these two cases, we use an approach similar to the one we have used for mileage calculation. Hence, the energy payment or charges in hour *h* can be defined as

$$\phi_h = \lambda_h \sum_{k=1}^{K} \sum_{n=1}^{N} \frac{\min\left\{\max\left\{0,\ c_{h,\tau_k}[\sigma_n]\right\}, \kappa_h^+\right\} - \max\left\{\min\left\{0,\ c_{h,\tau_k}[\sigma_n]\right\}, -\kappa_h^-\right\}}{NK} +$$
$$+ \sum_{k=1}^{K} \zeta_{h,\tau_k} \sum_{n=1}^{N} \frac{\max\left\{\max\left\{0,\ c_{h,\tau_k}[\sigma_n]\right\}, \kappa_h^+\right\} - \min\left\{\min\left\{0,\ c_{h,\tau_k}[\sigma_n]\right\}, -\kappa_h^-\right\} - 2\kappa_h^+}{NK}$$

where $\lambda_h$ is an hourly *LMP* in hour *h* at the bus, connected to *FES*, $\zeta_{h,\tau_k}$ is a real-time *LMP* at subperiod $\tau_k$ in hour *h* at the same bus.

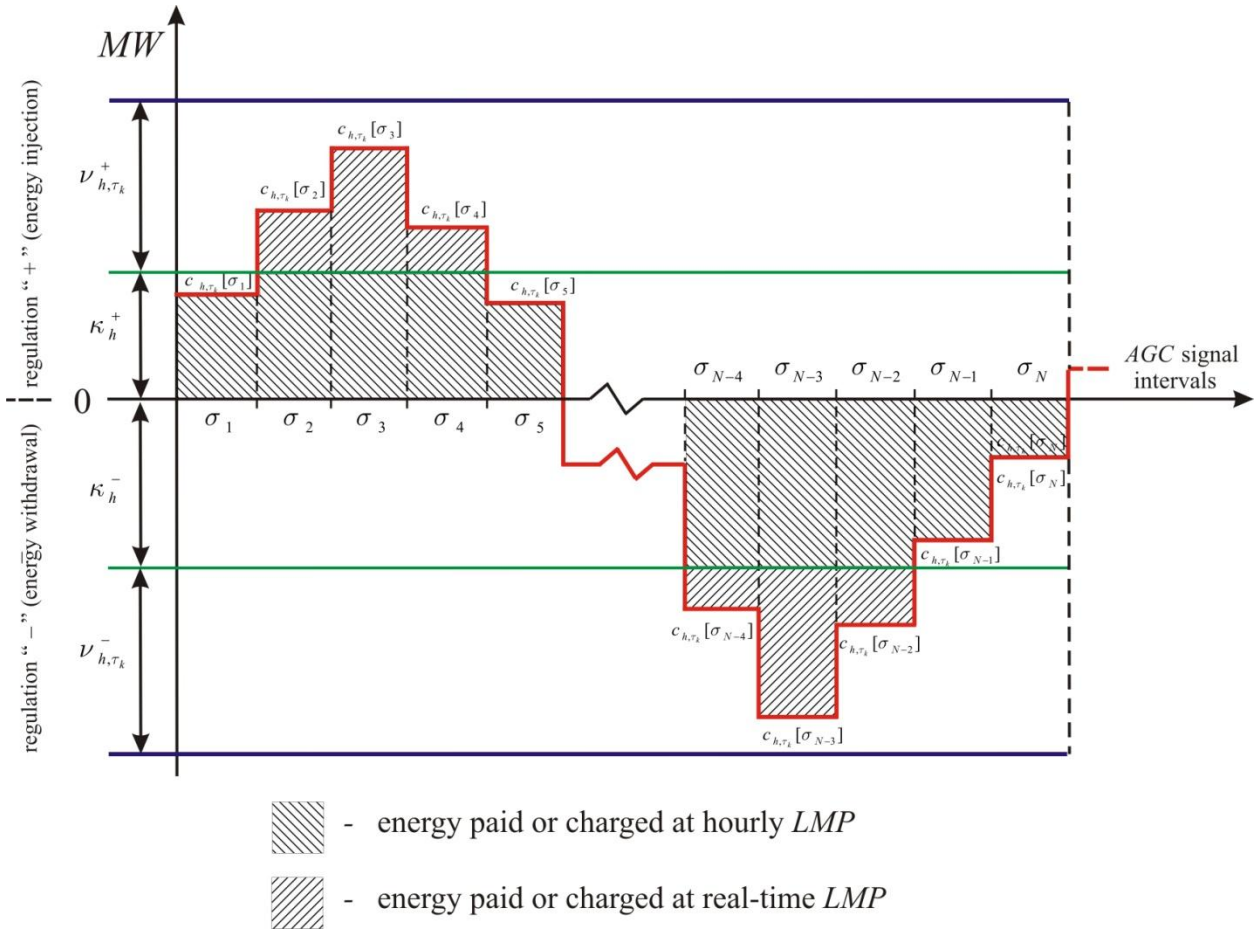


Figure B.3: Net energy payment

# APPENDIX C
# OVERVIEW OF THE SIMULATION APPROACH

The overview of market simulation algorithm for day *d* is shown on Figure C.1

For each day *d* in the simulation period, we first determine the regulation *DAM* offers which have resulted from solving the optimization problem $\mathcal{M}(\mathcal{H}')$, $\forall \mathcal{H}' \in \mathcal{H}$. This *DAM* schedule information is the input to the real-time offer problem $\mathcal{R}_{h\in\mathcal{H}}(\tau_k)$. The outcome of the *RTM* offer problem $\mathcal{R}_{h\in\mathcal{H}}(\tau_k)$ consists of the capacity offers in up and down directions for real-time subperiod $\tau_k$. Assuming *FES* price-taking behavior in *DAM* and *RTM*, all real-time and day-ahead regulation offers are cleared as submitted. Hence, the market clearing results define the contribution of total *AGC* service which the regulation unit is obligated to provide [44]. Therefore, the *AGC* curve is normalized based on combined *DAM* and *RTM* capacity rewards. The simulated *AGC* signal determines the unit's stored energy at the end of subperiod $\tau_k$ which is the same as the energy at the beginning of subperiod $\tau_{k+1}$. The process is repeated for each real-time subperiod $\tau_k \in h$ and for every hour $\forall h \in \mathcal{H}$. From day *d* day-ahead and real-time offers, regulation unit's actual performance, and regulation service clearing prices we calculate the *FES* capacity, mileage and energy payments using the settlement scheme presented in Appendix B. These figures form the basis of an economic assessment and comparative analysis of *DAM* and *RTM* offer strategies.

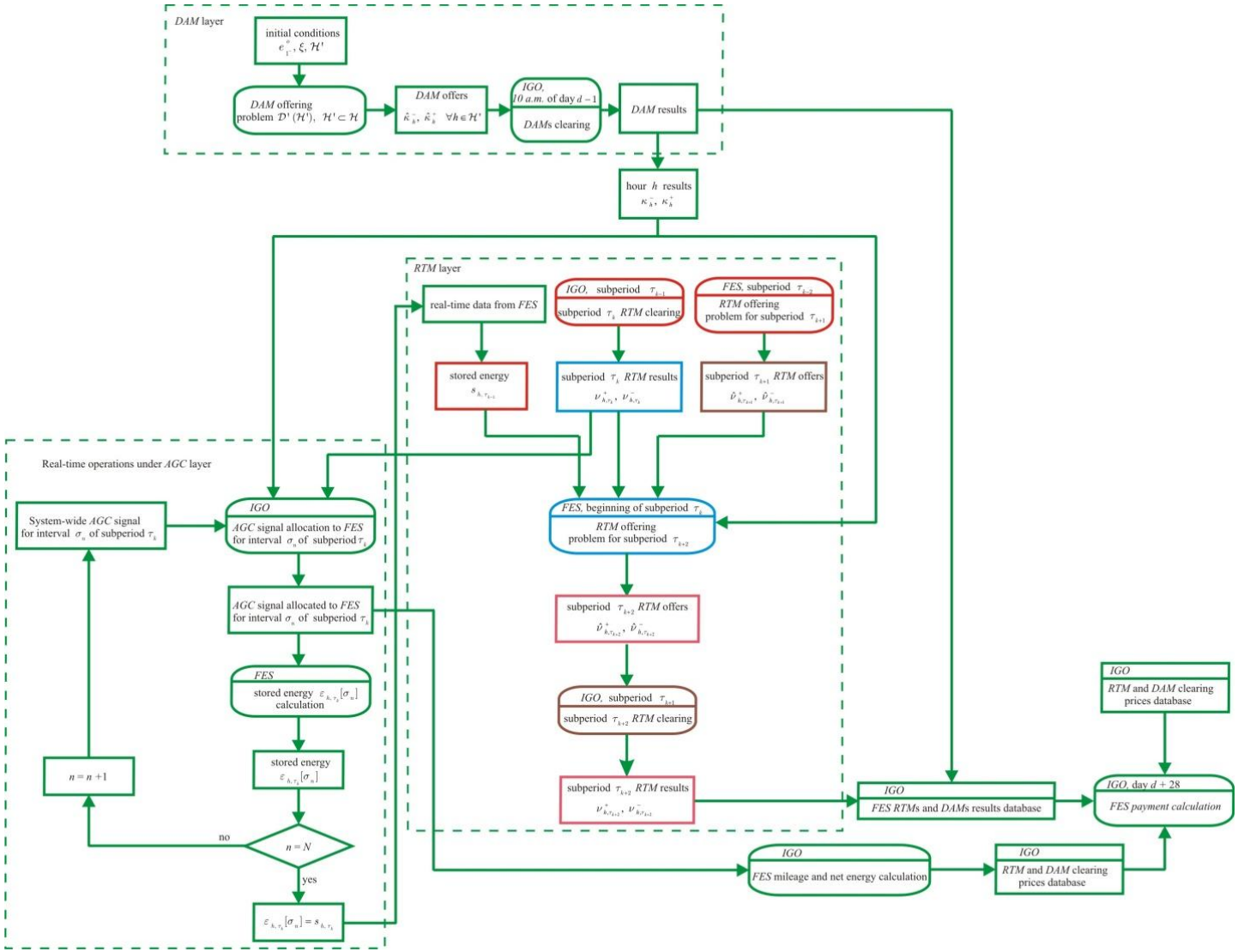


Figure C.1: Day-ahead and real-time offer strategies simulation algorithm

# REFERENCES


[1] B. J. Kirby, "Frequency regulation basics and trends," Oak Ridge National Laboratory, Oak Ridge, TN, Tech. Rep. ORNL/TM-2004/291, Dec. 2004.

[2] R. H. Byrne and C. A. Silva-Monroy, "Estimating the maximum potential revenue for grid connected electricity storage: Arbitrage and regulation," Sandia National Laboratories, Albuquerque, NM, Tech. Rep. SAND2012-3863, Dec. 2012.

[3] S. Lu, P. V. Etingov, D. Meng, X. Guo, C. Jin, and N. Samaan, "NV energy large-scale photovoltaic integration study: Intra-hour dispatch and AGC simulation," Pacific Northwest National Laboratory, Richland, WA, Tech. Rep. PNNL-22069, Jan. 2013.

[4] R. Masiello et al., "Research evaluation of wind generation, solar generation, and storage impact on the California grid," Kema Inc., Arnhem, Netherlands, Tech. Rep. CEC-500-2010-010, June 2010.

[5] J. Eyer, "Benefits from flywheel energy storage for area regulation in California – Demonstration results," Sandia National Laboratories, Albuquerque, NM, Tech. Rep. SAND2009-6457, Oct. 2009.

[6] FERC, "Order no. 755: Frequency regulation compensation in the organized wholesale power markets," 137 FERC 61,064, Federal Energy Regulatory Commission, Oct. 2011. [Online]. Available: http://www.ferc.gov/whats-new/comm-meet/2011/102011/E-28.pdf

[7] FERC, "Order no. 764: Integration of variable energy resources," 139 FERC 61,246, Federal Energy Regulatory Commission, June 2012. [Online]. Available: http://www.ferc.gov/whats-new/comm-meet/2012/062112/E-3.pdf

[8] I. Ibraheem, P. Kumar, and D. P. Kothari, "Recent philosophies of automatic generation control strategies in power systems," *IEEE Trans. Power Syst.*, vol. 20, no. 1, pp. 346-357, Feb. 2005.

[9] S. K. Aditya and D. Das, "Battery energy storage for load frequencycontrol of an interconnected power system," *Elect. Power Syst. Res.*, vol. 58, no. 3, pp. 179–185, Jul. 2001.

[10] S. C. Tripathy, R. Balasubramanian, and P. S. C. Nair, "Adaptive automatic generation control with superconducting magnetic energy storage in power systems," *IEEE Trans. Ener. Conver.*, vol. 7, no. 3, pp. 434-441, Sep. 1992.

[11] C. Guille and G. Gross, “A conceptual framework for the vehicle-to-grid (V2G) implementation,” *Energy Policy*, vol. 37, issue 11, pp. 4379-4390, Nov. 2009.

[12] T. Sasaki, T. Kadoya, and K. Enomoto, “Study on load frequency control using Redox flow batteries,” *IEEE Trans. Power Syst*., vol. 19, no. 1, pp. 660–667, Feb. 2004.

[13] B. Roberts, “Capturing grid power,” *IEEE Power and Ener. Magazine*, vol. 7, no. 4, pp. 32-41, July-Aug. 2009.

[14] A. Keyhani and A. Chatterjee, “Automatic generation control structure for smart power grids,” *IEEE Trans. on Smart Grid*, vol. 3, no. 3, pp. 1310-1316, Sept. 2012.

[15] Y. Chen, M. Keyser, M. Tackett, and X. Ma, “Incorporating short-term stored energy resource into Midwest ISO energy and ancillary service market,” *IEEE Trans. Power Syst*., vol. 26, no. 2, pp. 829-838, May 2011.

[16] G. Mallesham, S. Mishra, and A. Jha, “Automatic generation control of microgrid using artificial intelligence techniques,” in *Proceedings on 2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 61-68.

[17] C.A. Baoneand C. DeMarco, “From each according to its ability: Distributed grid regulation with bandwidth and saturation limits in wind generation and battery storage,” *IEEE Trans. Contr. Syst. Techn*., vol. 21, no. 2, pp. 384-394, Mar. 2013.

[18] M. Datta and T. Senjyu, “Fuzzy control of distributed PV inverters/energy storage systems/electric vehicles for frequency regulation in a large power system,” *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 479-488, Mar. 2013.

[19] A. Thatte, F. Zhang, and L. Xie, “Coordination of wind farms and flywheels for energy balancing and frequency regulation,” in *Proceedings on 2011 IEEE Power and Energy Society General Meeting*, 2011, pp. 23-30.

[20] H. Asano, K. Yajima, and Y. Kaya,“Influence of photovoltaic power generation on required capacity for load frequency control,” *IEEE Trans. Energy Conv*., vol. 11, no. 1, pp. 188-193, Mar. 1996.

[21] P. D. Brown, J. A. Peças Lopes, and M. A. Matos, "Optimization of pumped storage capacity in an isolated power system with large renewable penetration," *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 523-531, May 2008.

[22] B. Yang, Y. Makarov, J. Desteese, V. Viswanathan, P. Nyeng, B. McManus, and J. Pease, “On the use of energy storage technologies for regulation services in electric power systems with significant penetration of wind energy,” in *Proceedings of 5th Intern. Conf. on European Elect. Market*, 2008, pp. 61-66.

[23] T. S. Bhatti and D. P. Kothari, “Variable structure load-frequency control of isolated wind-diesel-microhydro hybrid power systems,” *Journ. Inst. Eng.*, vol. 83, pp. 52-56, 2002.

[24] M. P. Antonishen et al., “A methodology to enable wind farm participation in automatic generation control using energy storage devices,” in *Proceedings of 2012 IEEE Power and Ener. Society Gen. Meeting*, pp. 139-142, 2012.

[25] C. Jin, S. Lu, N. Lu, and R. A. Dougal, "Cross-market optimization for hybrid energy storage systems," in *Proceedings of IEEE Power and Energy Society General Meeting*, 2011.

[26] J. Donadee and M. Ilic, “Stochastic co-optimization of charging and frequency regulation by electric vehicles,” in *Proceedings of North American Power Symposium (NAPS)*, 2012.

[27] B. Bakken and K. Uhlen, “Market based AGC with online bidding of regulating reserves,” in *Proceedings of Power Engin. Society Summer Meeting*, 2001, pp. 848-853.

[28] K. Vu, R. Masiello, and R. Fioravanti, “Benefits of fast-response storage devices for system regulation in ISO markets,” in *Proceedings of IEEE Power and Energy Society General Meeting*, 2009, pp. 366-374.

[29] M. Lazarewicz and A. Rojas, “Grid frequency regulation by recycling electrical energy in flywheels,” in *Proceedings of IEEE Power Engineering Society General Meeting*, 2004, pp. 2038-2042.

[30] M. Lazarewicz and J. Arseneaux, “Status of pilot projects using flywheels for frequency regulation,” in *Proceedings of IEEE Power Engineering Society General Meeting*, 2006, pp. 938-941.

[31] California ISO Implementation Plan, *Non-Generator Resource Regulation Energy Management Project*, California ISO, 2012.

[32] I. Quirk, Comments of Pacific Gas and Electric company on regulation energy management draft tariff. PG&E, CA. [Online]. Available: http://www.caiso.com/Documents/PGECommentsonRegulationEnergyManagementRevisedDraftTariffLanguage.pdf

[33] P. Kundur, *Power System Stability and Control*. New York, NY: McGraw-Hill, 1994.

[34] J. Machovski, J.W. Bialek, and J. R. Bumby, *Power System Dynamics: Stability and Control*, 2nd ed. John Wiley & Sons, 2008.

[35] N. Cohn, *Control of Generation and Power Flow on Interconnected Power Systems*. Hoboken, NJ: John Wiley & Sons, 1966.

[36] D. N. Ewart, “Automatic generation control: Performance under normal conditions,” in *Systems Engineering for Power: Status and Prospects*, 1975, pp. 1-14.

[37] R. H. Miller and J. H. Malinowski, *Power System Operation*, 3rd ed. New York, NY: McGraw-Hill,1994.

[38] A. J. Wood and B. F. Wollenberg, *Power Generation, Operation, and Control*, 2nd ed. New York, NY: McGraw-Hill, 1996.

[39] A. Papalexopoulos and P. Andrianesis, “Performance-based pricing of frequency regulation in electricity markets,” *IEEE Trans. Power Syst*., vol. 29, no. 1, pp. 441-449, Jan. 2014.

[40] F. P. Sioshansi, *Competitive Electricity Markets: Design, Implementation, Performance*. Amsterdam: Elsevier, 2008.

[41] Y. Makarov, C. Loutan, J. Ma, and P. Mello, "Operational impacts of wind generation on California power systems," *IEEE Trans. Power Syst*., vol. 24, no. 2, pp. 1039-1050, May 2009.

[42] National Renewable Energy Laboratory, “20% windpower by 2030: Increasing wind energy’s contribution to U.S. electricity supply,” report DOE/GO-102008-2567 prepared for the U.S. Department of Energy, July 2008. [Online]. Available: http://www.nrel.gov/docs/fy08osti/41869.pdf

[43] D. Tretheway, (2012, Jan) “Pay for performance regulation, market design proposal.” California ISO. [Online]. Available: http://www.caiso.com/informed/Pages/StakeholderProcesses/PayforPerformanceRegulation.aspx

[44] D. Sathans and A. Swarup, “Automatic generation control of two area power system with and without SMES: From conventional to modern and intelligent control,” *International Journal of Engineering Science and Technology*, vol. 3, no. 2, pp. 3693-3707, May 2011.