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Optimal Regulation Provision by Aluminum Smelters

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Abstract—The industrial electrolysis process which is used to produce aluminum is a highly energy-intensive process. As it is possible to adjust the power consumption of this process on short notice without significantly affecting the quality of the aluminum, aluminum smelting plants are able to provide regulation to the electric power grid. In this paper, we focus on determining the optimal regulation capacity that such a manufacturing plant should provide to maximize the combined profit from producing aluminum and providing regulation. The approach is based on stochastic optimization and the stochastic variable is the regulation signal sent to the smelter. Using linear approximations of the high-resolution regulation signal as scenarios, we can reduce the computational burden to solve the associated optimization problem significantly. Simulations for a specific aluminum smelting plant provide insights into the optimal regulation provision by smelters with various cost and price parameters.

Index Terms—Demand response, Regulation, AGC, Stochastic programming, Industrial load.

I. NOMENCLATURE

H	set of hours
I	set of 5-minute intervals
S	set of AGC signal scenarios
K_s	set of AGC events in scenario s
L	set of production lines
J	set of production jobs
V_h	regulation capacity in hour h
$z_{l,i}$	scheduled tap position for line l in interval i
$m_{l,s,k}$	tap movement of line l in scenario s at event k
p_s	probability of scenario s
$X_{s,k}$	magnitude of AGC event k in scenario s
$t_{s,k}$	time that AGC event k occurs in scenario s
θ_l	power adjustment per step for line l
τ_l	time to move one step for line l
z_l^{up}, z_l^{lo}	tap position bounds for line l
$V_{l,i}^+, V_{l,i}^-$	available capacity for line l at interval i
P_l^0	base power consumption at zero tap
W_j	minimum power consumption of job j
λ_h^E	profit of energy consumption during hour h
λ_l^{Tap}	cost of control for line l
λ_h^P	penalty of control error in hour h
λ_h^V	profit for regulation capacity in hour h

II. INTRODUCTION

A major global challenge in the coming decades is the decarbonization of the electric energy system which will require the integration of a large share of renewable generation resources such as wind turbines and solar panels. However, the power output from these resources are uncertain and can not be controlled like conventional generation. Hence, dispatchable

resources are needed to balance the variable power output. A potential source to balance this variability is an increased participation of demand response in power systems [1] [2].

Utilities are developing demand response programs to encourage electricity consumers to actively participate in the power grid. Hence, research focuses on determining the potential resources of individual demand response and the integration of these resources into power system. For instance, [3] and [4] investigate the coordination of PHEV charging with other controllable loads and cogeneration units; [5] and [6] discuss the demand response provided by commercial buildings; [7] and [8] investigate the interaction and coordination of utilities and customers.

There has also been particular interest in the participation of industrial loads in demand response. In [9], the technical and economic potential of energy intensive industries to provide demand response in Germany is discussed. Chloralkali processes, mechanical wood pulp production, electric arc furnaces, aluminum electrolysis and cement milling are identified as promising sources for demand response. Detailed discussions of the industrial sector and its role in demand response including food processing plants and greenhouses can be found in [10] and [11]. In [12] and [13], the chemical engineering community has proposed scheduling methods for industrial plants taking into account the impacts of electricity markets and varying electricity prices.

Electrolysis is an energy intensive chemical process which is flexible enough to react to continuous requests to increase or decrease its energy consumption on a very short term basis. Consequently, it is a promising resource for demand response from industry. This includes both chloralkali and aluminum electrolysis. Alcoa's Warrick Operation is already providing regulation service to MISO [14]. Specifically, the plant installed communication and control systems to meet the requirements to participate in regulation which is generally implemented using Automatic Generation Control (AGC). Similar to generators, the aluminum production plant receives the AGC signal and adjusts its power consumption according to the signal. This project is considered to be the pilot project for the provision of regulation services by any industrial processing plant. In this paper, we propose a method which allows a plant with an electrolysis process to optimally determine the regulation capacity it should provide. The approach is based on the physical model of the process and its integration into a stochastic optimization problem in which the simplified AGC signal is the stochastic input variable.

III. PROBLEM STATEMENT

In ancillary service markets, a market participant bids its hourly regulation capacity and the desired price. The bid

and the clearing price are determined by the market operator after collecting offers from all market participants [15]. The participant should provide both positive and negative capacities indicating that if a manufacturing plant wants to provide regulation, it needs to operate below its full production capacity to ensure the ability to follow regulation in both directions. This regulation capacity is required by most ISOs to remain the same for the entire hour. In our formulation, we assume that positive and negative capacities are equal, but this could easily be relaxed. The plant also needs to provide a prediction of its energy consumption for the next hour in a resolution of 5 minutes, i.e. 12 predicted values for the hour. These predictions serve as the baseline for the regulation performance evaluation. This power prediction reflects the plant's production schedule if no regulation is provided.

Aluminum smelter and other electrolysis plants are able to adjust their power consumption by adjusting tap changers in the rectifier stations that supply DC energy to the production lines. The tap positions can be changed quickly and accurately, enabling the provision of fast and precise regulation. Though the chemical relationship within electrolysis is fairly complex [16] and the traditional view for over almost a century has been that keeping current and voltage stable was critical for a stable and efficient aluminum production, it has been demonstrated that the voltage of each potline can be changed very frequently at Alcoa's Warrick Operation, providing regulation service while carrying on electrolysis production at the same time [14].

Once the plant is cleared for a certain regulation capacity, the plant receives compensation for the lost opportunity of electrolysis production by being paid for the provision of regulation capacity. It is obliged to fully respond to AGC commands within that capacity range, otherwise a non-performance penalty is imposed and the performance scoring is affected. Regulation performance scoring in practice may be very complicated to determine [17], hence, here we simplify the calculation by only penalizing the difference between AGC command and regulation mileage. In its cost/benefit optimization, the industrial plant also needs to take into account its own production costs such as labor cost, product sales, energy cost, rectifier station degradation and so on.

To simplify the problem, we made the following assumptions for the considered electrolysis process:

Assumption 1: The production rate is proportional to the power consumption and the power consumption is proportional to the voltage at the rectifier which controls the electrolysis process. The voltage on the other hand is linearly dependent on the rectifier tap changer position.

Assumption 2: The regulation revenue is proportional to the cleared capacity, the production revenue is proportional to the energy consumed, the control cost is proportional to the tap movement and the performance penalty is proportional to the difference between regulation command and mileage. All those prices are assumed to be parameters.

IV. AGC SIGNAL SIMPLIFICATION

Automatic generation control regulates the power output of generators to balance generation and load momentarily.

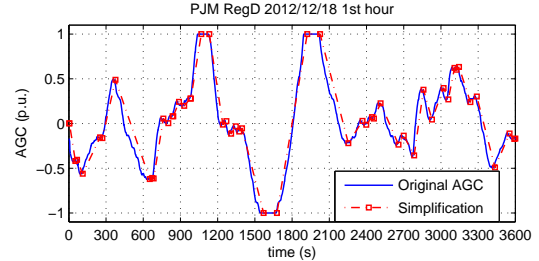


Fig. 1. Simplification of AGC Signals. The red square dashed line represents the linear simplification. The blue solid line represents the original PJM's RegD signals of the first hour on 12/18/2012 [18].

It is expected that in the future a greater contribution of such regulation is provided by storage and flexible demand. The AGC commands are sent by the control center based on the real time power system conditions. The regulation provider commits to responding to the commands which are sent every 2s or 4s. The p.u. AGC signal multiplied by the provided regulation capacity is the AGC command that the plant committed to follow.

Given the high resolution of the AGC signal it is very difficult if not impossible to predict the signal for a longer time frame. However, as we intend to use stochastic optimization to determine the optimal regulation capacity, we need to find a way to generate scenarios and capture the expected regulation provision without having an accurate prediction of the AGC signal. Hence, we propose a linear simplification of AGC signals by local extreme points and then create scenarios based on such extreme points. First, we apply a low pass filter to the original AGC signal to remove high frequency noise. Local extreme points are then identified by numerical derivatives along the curve, i.e. whenever the derivative changes its sign, a local extreme point has been detected. Successive local extreme points that fall within short distances both in time and magnitude, e.g. time gaps less than 5s and value gaps less than 0.025p.u., are further aggregated as one single point. Hence, local extreme points which will be called AGC events in the remainder of the paper are identified and used for scenario generation. Piecewise segments characterized by those AGC events serve as a linear simplification of the AGC signal in between extreme points as shown in Fig. 1.

This simplification approximates the real trajectory of the AGC signal by piecewise linear segments. The statistics of the AGC events' magnitude and time interval are provided in Fig. 2 and Fig. 3. Typically around 40 - 60 AGC events are presented in an hour's worth of regulation D signal. Given the original scenarios of AGC signals, we apply the simplification and obtain the simplified scenarios. Then, the proposed model only responds to AGC events of the simplified scenarios and tracks the piecewise linear trajectory. The approximation here is reasonably sound and is able to reduce the computational burden in the stochastic optimization significantly.

V. OPTIMAL REGULATION CAPACITY

In this section, the proposed optimal capacity provision model is presented by which the plant decides its hourly regulation capacity V_h that would be optimal for the plant for the upcoming operating period. We focus on the regulation provision from the industrial electrolysis process and optimize

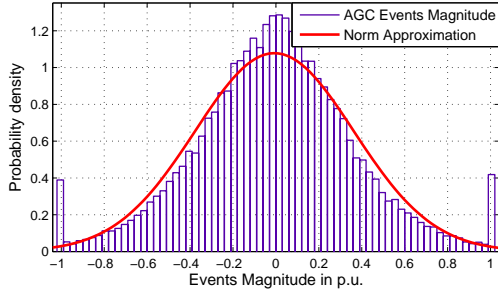


Fig. 2. Histogram of AGC Events' Magnitude. The AGC events are simplifications of PJM's RegD Signals from 12/18/2012 to 01/18/2013 [18].

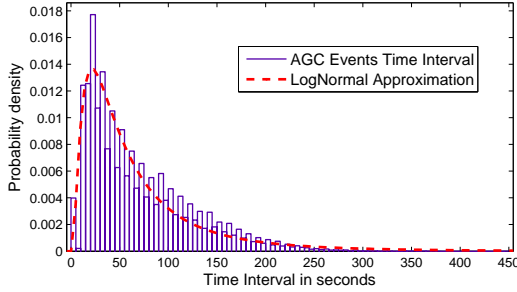


Fig. 3. Histogram of AGC Events' Time Interval - the time between two successive AGC events.

its participation. Future work will focus on building a bidding curve which the plant should bid into the market. As of now, we determine the capacity that the plant ideally is cleared for, assuming that the price it will receive has been predicted reasonably well. Power flow constraints are not considered, as we do not study the overall system in this paper. The plant first needs to submit its predicted power consumption for every 5 minutes of the next hour. These values serve as a baseline for the regulation provision and basically correspond to the scheduled rectifier tap changer positions $z_{l,i}$. The regulation command it needs to follow is equal to the multiplication of V_h and $X_{s,k}$ where s indicates the scenario and k the k -th AGC event. In order to follow this command, the tap position of the rectifier of production line l moves by $m_{l,s,k}$ steps from its original position $z_{l,i}$. The rectifier tap positions evolve in a discrete manner, hence, $z_{l,i}$ and $m_{l,s,k}$ are integer variables. However, since the number of $m_{l,s,k}$ grows with the number of scenarios and trajectory simplification is adopted, $m_{l,s,k}$ is relaxed and assumed to be continuous in order to simplify the calculations.

A. Constraints

1) *Rectifier Tap Changer*: Rectifier tap changers are designed to operate within a certain range. In addition, changing the tap position is a mechanical process which means that there is a limit on how much change can be achieved within a certain amount of time. Consequently, the following constraints need to hold for $\forall l \in L, i \in I, s \in S, k \in K_s$:

$$z_l^{lo} \leq z_{l,\mathcal{I}(k)} + m_{l,s,k} \leq z_l^{up} \quad (1)$$

$$dz_{l,s,k} = |z_{l,\mathcal{I}(k+1)} + m_{l,s,k+1} - z_{l,\mathcal{I}(k)} - m_{l,s,k}| \quad (2)$$

$$dz_{l,s,k} \cdot \tau_l \leq t_{s,k+1} - t_{s,k} \quad (3)$$

where $\mathcal{I}(\cdot)$ is a function mapping event k to its corresponding 5min interval i .

2) *Regulation Capacity*: The maximum regulation capacity is the summation of available capacities over all production lines. However, this capacity needs to remain the same for the entire hour which is limited by the available capacity within every 5min interval. For $\forall l \in L, i \in i(h)$, the following constraints need to hold:

$$V_{\mathcal{H}(i)} \leq \sum_{l \in L} V_{l,i}^+ \quad (4)$$

$$V_{\mathcal{H}(i)} \leq \sum_{l \in L} V_{l,i}^- \quad (5)$$

$$V_{l,i}^+ \leq \theta_l \cdot (z_l^{up} - z_{l,i}) \quad (6)$$

$$V_{l,i}^- \leq \theta_l \cdot (z_{l,i} - z_l^{lo}) \quad (7)$$

where $\mathcal{H}(\cdot)$ is a function mapping the 5min intervals i to its corresponding operating hour h .

3) *Plant Scheduling*: The main purpose of the plant is to carry out electrolysis and produce aluminium. Hence, we impose a constraint which ensures that production targets are met. Since production is proportional to electricity consumption, the constraint can be formulated as a lower constraint on the energy consumption of the plant. Hence, for $\forall j \in J, s \in S$:

$$\sum_{l \in L} \sum_{k \in \mathcal{K}(j)} ((z_{l,\mathcal{I}(k)} + m_{l,s,k}) \cdot \theta_l + P_l^0) \cdot \mathcal{T}(k) \geq W_j \quad (8)$$

where $\mathcal{K}(j)$ stands for all AGC events that occur during production task j . $\mathcal{T}(\cdot)$ is a function that calculates the time duration for each AGC event k . For event k in scenario s , $\mathcal{T}(\cdot)$ returns $(t_{s,k+1} - t_{s,k-1})/2$, i.e. the time duration it affects the energy consumption. This constraint should hold for every scenario making sure the plant's minimum production level is ensured.

B. Objective

The overall objective of the optimization problem is a sum of multiple cost and revenue terms.

1) *Energy Consumption*: The value λ_h^E denotes the per unit profits made by consuming electricity and producing aluminium, which includes the revenue from selling aluminium and the combined costs of producing aluminium. That part of the objective function is given by

$$EProfit = \sum_{s \in S} p_s \sum_{l \in L} \sum_{k \in K_s} \theta_l (z_{l,i(k)} + m_{l,s,k}) \mathcal{T}(k) \lambda_h^E \quad (9)$$

2) *Control Action*: There is a limit on how much the tap of a rectifier could be changed because intensive movement leads to frequent replacement of the rectifiers. The price λ_l^{Tap} reflects the average cost per movement resulting in the following contribution to the overall objective

$$ACost = \sum_{s \in S} p_s \sum_{l \in L} \sum_{k \in K_s} dz_{l,s,k} \lambda_l^{Tap} \quad (10)$$

3) *Deployment Error*: As a demand resource, the regulation deployment is the negative summation of all tap changers multiplied by the change in energy consumption per tap step, thus the regulation error $\delta_{s,k}$ is equal to:

$$\delta_{s,k} = |X_{t,s} V_h + \sum_{l \in L} \theta_l m_{l,s,k}|$$

and the resulting penalty is given by:

$$Penalty = \sum_{s \in S} p_s \sum_{k \in K_s} \delta_{s,k} \lambda_{\mathcal{H}(\mathcal{I}(k))}^P \quad (11)$$

TABLE I
POTLINE PARAMETERS

l	θ_l/MW	τ_l/s	z_l^{up}	z_l^{lo}	P_l^0/MW
1	0.8	5	10	-10	100
2	1.2	5	9	-9	100

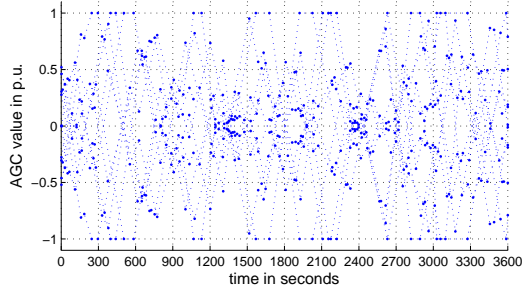


Fig. 4. Simplified AGC Signal Scenarios. Five scenarios are taken from the first hour's PJM Regulation-D signals from 2012/12/18 to 2012/12/22 [18]. These five scenarios and their negative constitute the original ten scenario AGC set that is positive and negative well balanced.

4) *Regulation Capacity*: The electrolysis plant receives a payment for the provision of its regulation capacity V_h , i.e. the plant's revenue from regulation provision is given by:

$$VRevenue = \sum_{h \in H} V_h \cdot \lambda_h^V \quad (12)$$

The overall objective function is given by the sum over all of these objectives resulting in:

$$\min -EProfit + ACost + Penalty - VRevenue \quad (13)$$

The resulting overall problem formulation is a mixed integer linear programming problem.

VI. SIMULATION

A. Hourly Regulation Provision

1) *Base Case*: We consider an aluminum smelter that optimizes its hourly regulation provision. It consists of two potlines for which the parameters are listed in Table I. Ten AGC scenarios are considered and it is assumed that the probability of occurrence of each scenario is the same. The linearized evolution of the AGC signal in these scenarios is shown in Fig. 4. There's one production task to complete within the considered hour and the minimum production is set to 95% of the base production which corresponds to the production achieved if the tap position is zero. The minimum regulation capacity required by the ISO is assumed to be 1MW.

In the following, we will carry out a range of simulations for different combinations of values for the price parameters. Hence, we define a price vector

$$\pi := (\lambda_h^E, \lambda_l^{Tap}, \lambda_h^P, \lambda_l^V)$$

to indicate the values for the individual parameters with units in \$/MWh, \$, \$/MW, \$/MW. For the base case, we choose π as (20,1.5,3,30). For this base case, the optimal regulation capacity is 17.6MW and the average power consumption over all scenarios is 200.68MWh. Fig. 5 gives more detailed results showing the evolution of the power production over the entire hour, the available regulation capacity and the deviations from the regulation signal.

TABLE II
RESULTS UNDER DIFFERENT PARAMETERS

π	V_h/MW	\bar{w}/MWh
(20, 1.5, 3, 30)	17.6	200.68
(10, 1.5, 3, 30)	18.8	199.40
(50, 1.5, 3, 30)	14.0	205.28
(100, 1.5, 3, 30)	9.6	211.71
(20, 0, 3, 30)	18.8	198.73
(20, 0.5, 3, 30)	17.6	199.66
(20, 5, 3, 30)	1.0	198.22
(20, 1.5, 1, 30)	18.8	203.07
(20, 1.5, 10, 30)	15.2	200.85
(20, 1.5, 20, 30)	10.8	200.50
(20, 1.5, 3, 10)	1.0	198.31
(20, 1.5, 3, 20)	10.8	200.38
(20, 1.5, 3, 40)	18.8	199.75

2) *Effects of Prices*: Now, individual values in π are varied to investigate the impact on optimal regulation capacity and energy consumption. The results are summarized in Table II. As the profit price increases, the average energy consumption grows indicating that the plant produces more aluminum. As the cost of tap movement increases, the optimal regulation capacity decreases. The same also holds for if the penalty on deviations from the requested AGC signal increases. In this case, concurrently with a decrease in regulation capacity, the regulation error decreases as shown in Fig. 6. Finally, as the compensation for regulation increases, the optimal regulation capacity increases.

B. Multi-hour Regulation Provision

In practice, the plant may have multiple hours to produce a certain amount of aluminum which adds some additional flexibility to the production schedule. Hence, here we carry out a three hour simulation with again 10 different scenarios for the AGC signal. It is assumed that it needs to produce at least 95% of the base production. The simulated price parameters π are (10,1.5,30) (50,1.5,10) (12,1.5,32) for the three hours which encourages regulation participation in the 1st and 3rd hour while encouraging increased production in the 2nd hour. The other parameters are same as in the base case. The results for the optimal regulation capacities are shown in Fig. 7 .

VII. CONCLUSION

This paper considers the regulation participation from industrial demand and proposes an optimal regulation capacity provision model for a given regulation price for electrolysis processing plants. The stochastic optimization model uses simplified AGC signal scenarios to consider the influence of regulation participation and takes into account the impact of different price settings on the decision of regulation capacity provision. Increasing the compensation for regulation capacity encourages higher capacity provision, while too expensive control cost or too high penalties on non-performance lead to low regulation participation. The simulation results suggest more electricity consumption (and therefore more aluminium production) and lower regulation participation when the profit price is higher.

The main contributions of this paper are: (a) proposing AGC signal simplification method that enables regulation participation analysis by a stochastic programming method with reasonable approximation and desirable computational

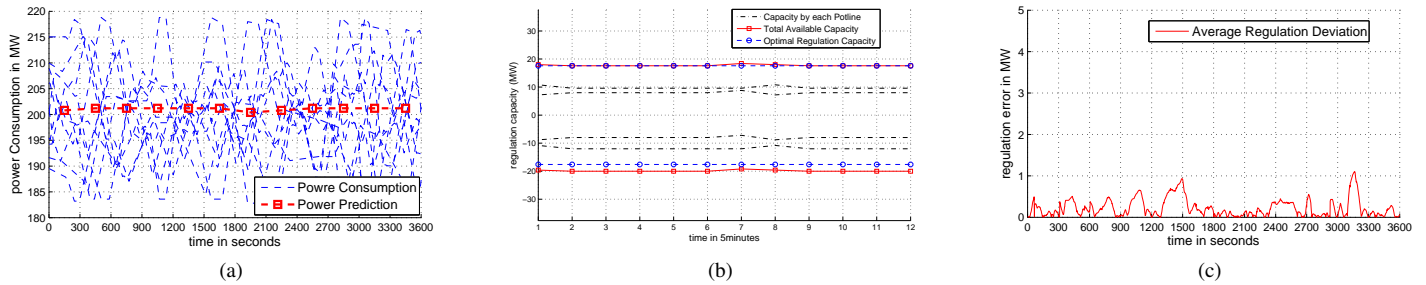


Fig. 5. Results under $\pi = (20, 1.5, 3, 30)$. (a) Power consumption: red square line represents power prediction baseline while blue dashed lines denote power consumption under scenarios. (b) Regulation Capacity: black dashed lines present available positive or negative capacities for each potline, red square lines represent total available capacities while blue circle lines display optimal capacity to provide. (c) Regulation Performance: the deviation between regulation mileage and original AGC command in each scenario is calculated on 2s basis and the average deviation over all scenarios is displayed as the red line.

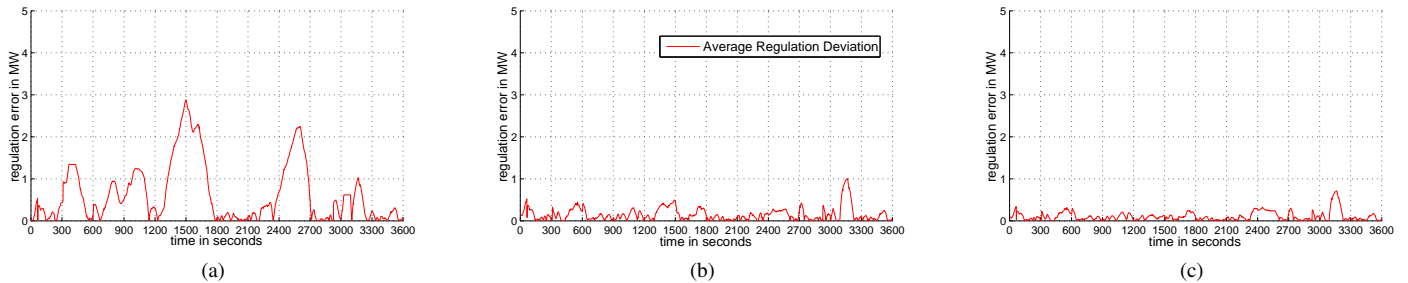


Fig. 6. Regulation Performance under $\pi = (20, 1.5, \lambda^P, 30)$: (a) $\lambda^P=1$, (b) $\lambda^P=10$, (c) $\lambda^P=20$. As penalty increases, the regulation accurateness improves.

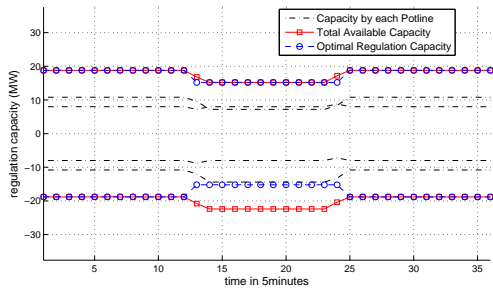


Fig. 7. Regulation Capacity for 3 hour case.

complexity; (b) optimizing regulation capacity provision for electrolysis processing plants which serves as a potential tool for practical operation. Future work includes further investigation of AGC data, bidding curve design and optimization for longer-term scheduling.

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