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Day Ahead Regulation Tool Final Report

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FINAL PROJECT REPORT

PREDICTING DAY-AHEAD REGULATION REQUIREMENTS FOR THE CAISO BALANCING AREA

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A CIEE Report

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PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Renewable Energy Technologies
- Transportation

This draft report is the final report for the "Predicting Day-Ahead Regulation Requirements for the CAISO Balancing Area" project (contract number: 500-07-037, work authorization number: POTRO1-X11) conducted by the Pacific Northwest National Laboratory. The information from this project contributes to PIER's Energy Systems Integration program area.

For more information about the PIER Program, please visit the Energy Commission's website at http://www.energy.ca.gov/research/, or contact the Energy Commission at 916-654-4878.

ABSTRACT

This report presents a new approach, methodology, and software developed by Pacific Northwest National Laboratory (PNNL) for procuring regulation capacity that would minimize the required regulation reserve for a particular operating hour of a day without compromising California Independent System Operator's (CAISO's) control performance characteristics. The approach is capable of predicting CAISO's regulation reserve requirement on a day-ahead basis by calculating regulating capacity, ramping rate and ramp duration requirements, including upward and downward requirements, for each operating hour of a day. Three methods have been implemented. In the first method, the probability distributions of area control error (ACE) components, including the interchange error component, frequency error component, metering error correction component, automatic time error correction component, and inadvertent interchange payback component, are evaluated separately and summed to evaluate the regulation requirement. The second method predicts regulation requirements based on a statistical analysis of area control error signals and applied regulation data. The third method is similar to the second, but is based on the new Balancing Authority ACE limit (BAAL) standard. A statistical approach based on the time-varying empirical probability density function (PDF) is used in all three methods to determine the regulation requirement. A moving window is defined to collect sufficient statistical information regarding probability distributions of the regulation requirement and its components. Based on the collected statistics, the approach evaluates the percentile intervals (also called confidence intervals or uncertainty ranges) for each operating hour based on a certain user-specified level of confidence. Actual CAISO operation data was used to validate the performance of all three methods. The results obtained by the three methods are presented and compared. Results show that using the proposed methods can save CAISO an average of 10% of its current regulation procurement, satisfying current control standards. With the new BAAL control standard imposed, the savings could reach 30%.

Keywords: Regulation reserve requirement, area control error, ancillary services, CPS, BAAL, solar generation, load forecast, wind generation forecast, probability density function, swinging door algorithm.

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Executive Summary

This research was conducted by Pacific Northwest National Laboratory (PNNL) for the California Energy Commission and the California Institute for Energy and Environment.

Regulation is a process of providing minute-to-minute system balance by adjusting the power output of generators connected to the automatic generation control (AGC) system. Regulation is an expensive resource, and the annual price of regulation significantly exceeds 120 million dollars in California.

Most of CAISO's "once-through cooling" generating units using along California's Pacific coast are expected to be retired or retrofitted within the next decade. These units have traditionally been used to provide balancing services for CAISO, and their retirement could potentially create a deficiency in available regulation resources. The consequent decline in available regulation resources could potentially increase the price of regulation as more regulation procurement is needed. These challenges motivate CAISO to obtain a tool capable of predicting the needed procurement of up- and down-regulation services in the day-ahead market.

The objective of this project is to develop an approach to procuring regulation capacity that would minimize the regulation capacity required during some operating hours without compromising CAISO's control performance characteristics. The chosen approach predicts CAISO's regulation requirement on a day-ahead basis by calculating the required regulating capacity, ramping rate (rate of change of the regulating units' output) and ramp duration (how long the ramp should be maintained), including upward and downward, for each operating hour of a day.

In this project, three methods were developed. The methods differ by the approach used to calculate the regulation requirement and by the type of control performance criteria used. The first and the second methods are close in philosophy to the existing control performance standard, CPS2, which limits ten-minute averages of the area control error (ACE) to below a certain value, L_{10}, specified by the North American Electric Reliability Corporation (NERC).

- The first method evaluates regulation requirements based on statistical analysis of all components of the regulation requirement: forecast errors (load, wind and solar generation), uninstructed generation unit deviations, frequency errors, and metering error correction.
- The second method predicts regulation requirements based on a statistical analysis of ACE signals and actual regulation applied in the system.
- The third method is based on a new standard that is currently under trial use in the industry. It evaluates the regulation requirement in order to meet the new Balancing Authority ACE Limit (BAAL) standard, by which instantaneous values of ACE are limited by frequency-sensitive ACE limits. Like Method 2, it is based on a statistical analysis of the actual ACE and frequency information.

Results obtained by the three methods are presented and compared in the report.

Figure 1 shows an example of CAISO's hourly regulation requirement prediction for 12/10/2010. Blue bars correspond to Method I, green bars represent regulation requirements calculated by Method II (for the 90% confidence level), and red bars show regulation requirements calculated by Method III to meet the new control BAAL performance standard. It can be seen from Figure 1 that CAISO regulation requirements can be essentially reduced due to the fact that the BAAL standard allows balancing authorities (BAs) to operate in a wider range of ACE values and consequently with less regulation compared with the previous CPS2 performance standard. The expected CAISO regulation ramping requirements on 12/10/2010 in terms of ramp rate and ramp duration are shown in

Figure 2. The heights of the bars reflect the maximum ramp rate and the widths of the bars indicate the maximum ramp duration requirements.

Figure 1. Expected CAISO Regulation Capacity Requirements for 12/10/2010 Calculated by Methods I, II, and III

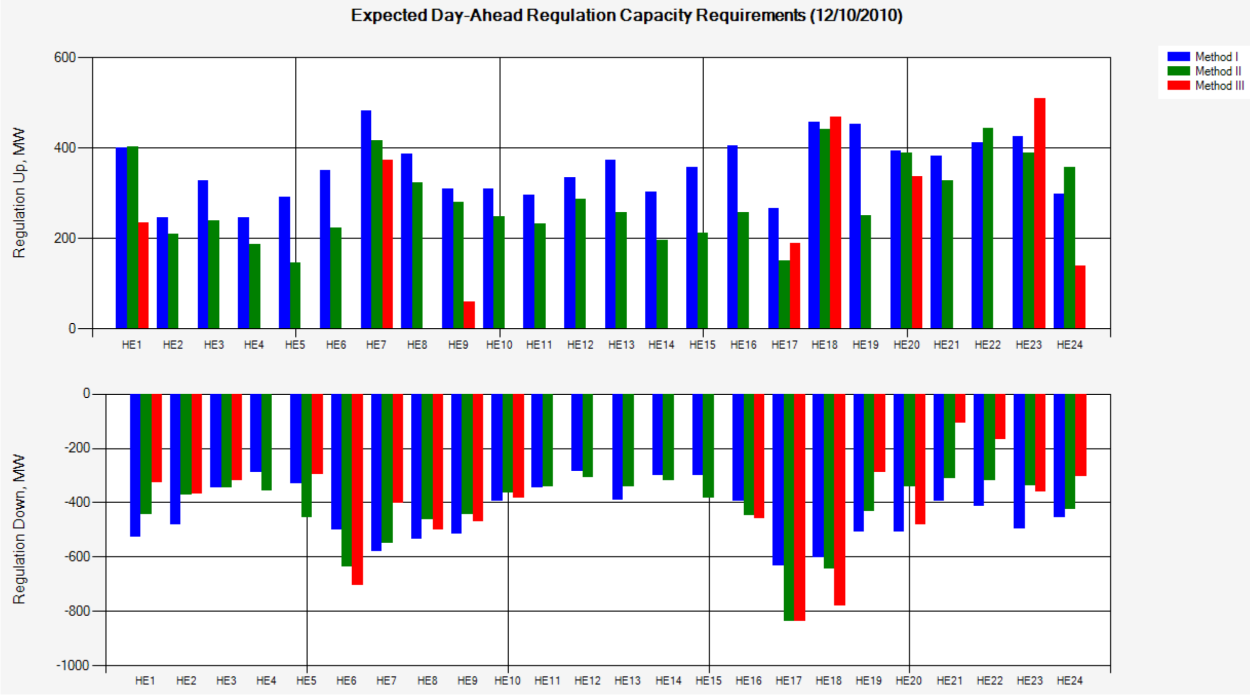


Figure 2. Expected CAISO Regulation Ramping Requirements for 12/10/2010

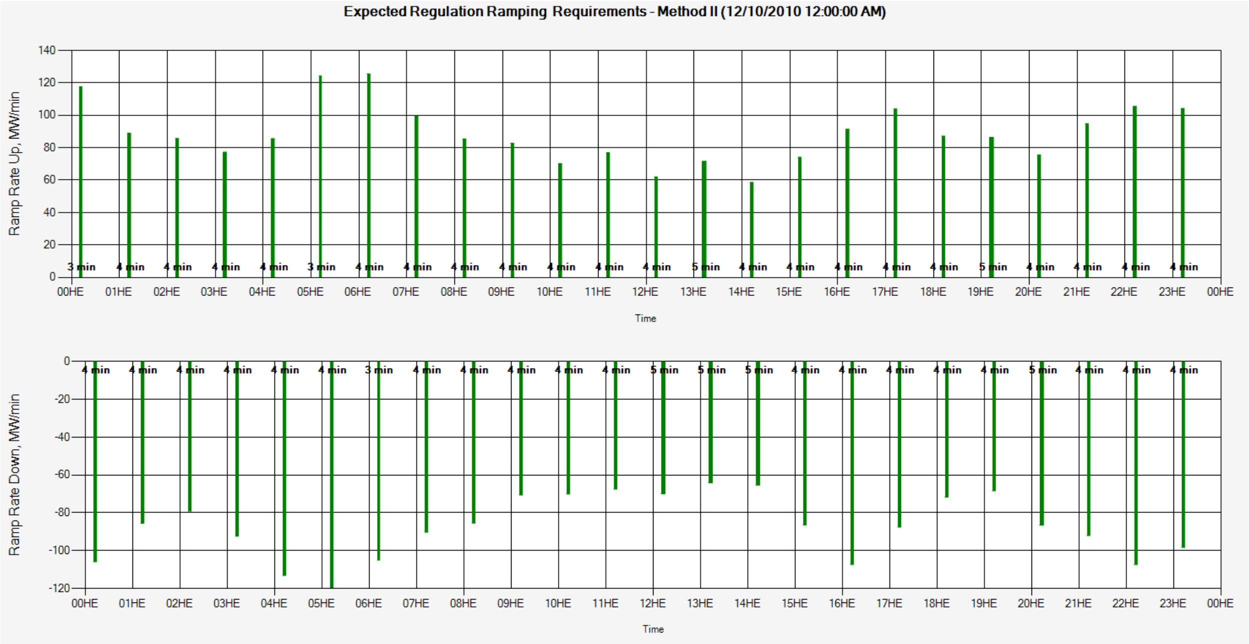


Figure 4 shows the "ideal" regulation requirements curve (dark red) for 12/10/2010. This curve corresponds to the regulation that would be needed to have constant zero ACE. The day-ahead regulation actually procured on 12/10/2011 is shown by the yellow range, and regulation requirement prediction (for a 90% level of confidence) is shown by the gray range.

An evaluation of these prediction results is also given in Table 1. The CAISO day-ahead regulation procurement covers only 83% of the regulation requirement points (Figure 4). At the same time 92% of the regulation requirement points (dark red curve) are within the regulation requirements prediction range (gray range). Total day-ahead regulation procurement cost on 12/10/2010 was more than $112,000. Using the regulation prediction requirements provided by Method II would have allowed the CAISO to save about $15,000 (13%) during this day.

Figure 4. Method II vs. CAISO Day-Ahead Regulation Procurement

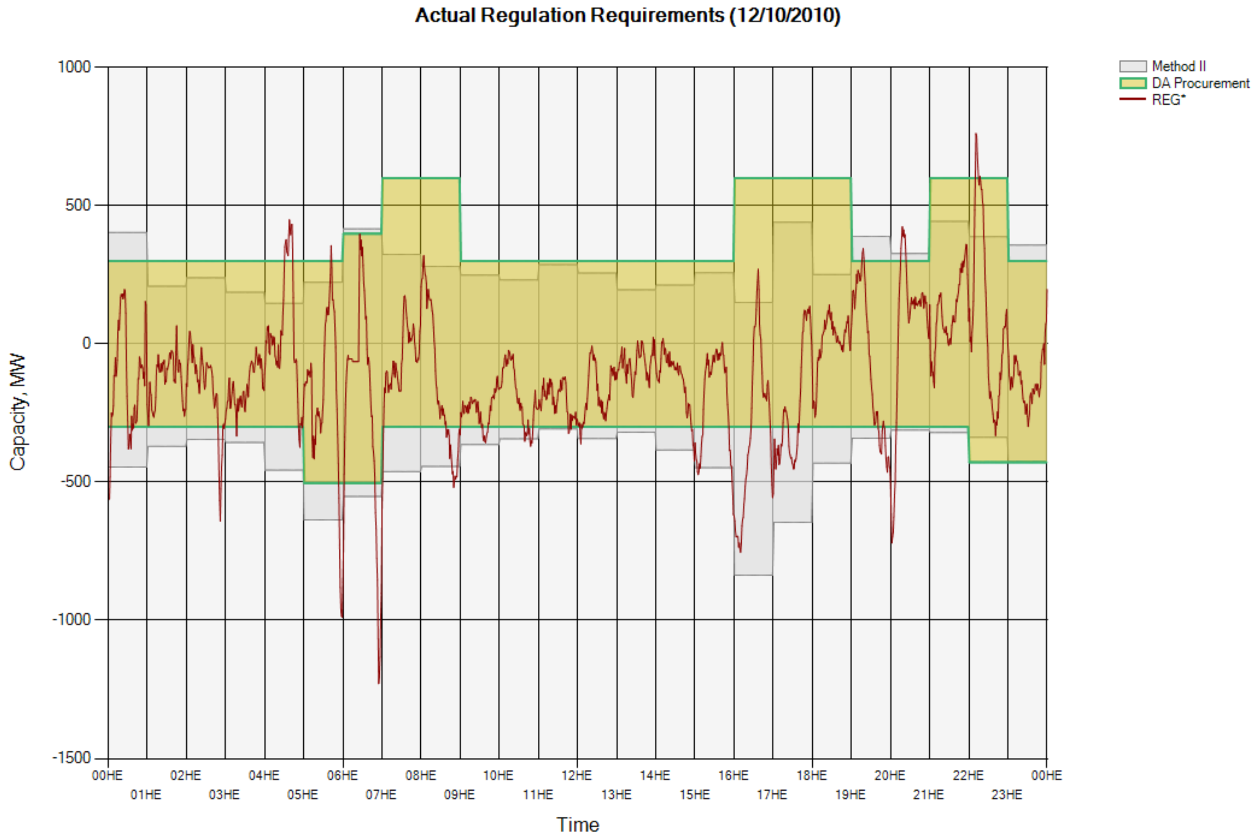
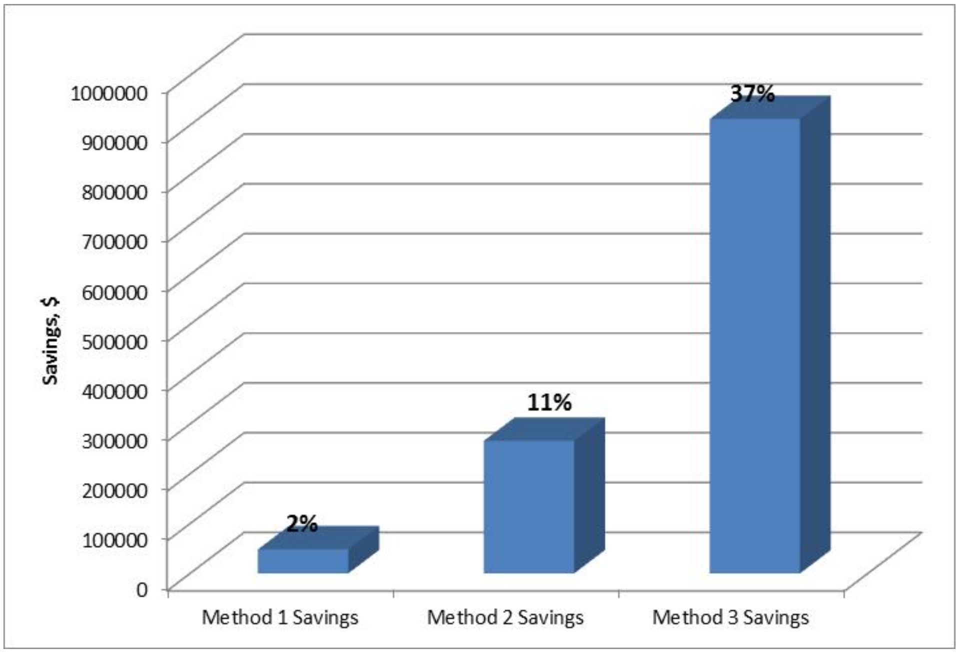


Table 1. Evaluation of Prediction Results (12/10/2010)

	Percentage of Points Within the Range	Regulation Procurement Total Cost
CAISO Day-Ahead Regulation Procurement	83%	$112,200
90% Confidence Regulation Requirements (Method II)	92%	$97,500
Potential Savings		$14,600 (13%)

An evaluation of the potential monthly savings is shown in Figure 5. The total monthly cost of regulation is about 2.5 million dollars. The average monthly savings for Method II is about 11%, or $250,000. Because the new BAAL standard allows a balancing area (BA) to operate in a wider ACE range, using regulation requirements calculated by Method III could potentially save as much as 30–40%. Of course, AGC algorithms should be adjusted to make use of the relaxed BAAL balancing criteria and the actual ACE value does not result in unscheduled flows among balancing authorities. It is also important to note that the potential saving achieved by Method III can be reduced due to other potential implications such as accumulation of inadvertent energy and associated costs.

Figure 5. Regulation Procurement Monthly Savings Under the Existing Procedure (Total Cost) Achieved by Using Methods 1-3[1]



The results of this project can be summarized as follows.

Three new methods have been developed and implemented to evaluate the day-ahead regulation reserve requirements:

- Method I is based on a statistical analysis of all sources of uncertainty (load, wind generation, solar generation, unit uninstructed deviations, frequency deviation, etc.)
- Method II is based on a statistical analysis of ACE and actual regulation applied to the system.
- Method III evaluates the regulation requirements based on compliance with the BAAL standard.
    - A methodology for estimating regulation requirements taking into account the new control performance standard (BAAL) has been developed.
    - Simulations have shown that CAISO regulation requirements can be essentially reduced because the BAAL standard allows a BA to operate in a wider ACE range compared with the previous CPS2 standard.
- All three methods are using historical information, obtained prior to the analyzed operating day (a moving window for a user-specified period).
- The performance of the proposed methods can be further improved by incorporating ramp and uncertainty information provided by the CAISO wind and solar forecast service providers.

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[1] The actual saving with Method III can be lees due to the other influencing factor such as impacts on interties and inadvertent accumulation.

A software tool has been developed, which includes a graphical user interface (GUI), algorithms for detecting and correcting input data outliers, an Oracle®-based database, and a self-validation procedure. The tool implements the following main features:

- prediction of hourly-specific regulation requirements for the next operating day, which can potentially help the CAISO to save money on regulation cost;
- detailed visualization of input data and results, making the process transparent and user friendly to the CAISO operators and engineers;
- flexibility (different confidence levels, moving-window sizes, etc.) allowing CAISO engineers to fine-tune the tool to their needs including the level of compliance with the existing control performance standards;
- self-validation of predicted results, providing a self-control feature for the accuracy of the algorithm;
- detection of outliers and statistical analysis of input data (distribution, standard deviation, mean value) to help in detecting and eliminating bad data.

CHAPTER 1: Introduction

Background

Regulation is the process of providing minute-to-minute system balance by adjusting power output of generating units connected to the automatic generation control (AGC) system. Regulation is typically the most expensive ancillary service. Recent studies of integrating renewable energy resources performed by the California Independent System Operator (CAISO) (CAISO 2010), indicated that regulation requirements will increase because of the variability and forecast uncertainty associated with the high penetration level of renewable resources such as wind and solar.

Most of CAISO's "once-through cooling" generating units along California's Pacific coast are expected to be retired or retrofitted within the next decade. These units have traditionally been used to provide balancing services for CAISO, and their retirement could potentially create some deficiency in available regulation resources. Consequently, the price of regulation would increase as more regulation procurement is needed while available resources providing this service decline. These challenges were instrumental in the CAISO's desire to have a tool that is capable of predicting the needed procurement of up- and down-regulation services in the day-ahead market.

Area Control Error (ACE)

The area control error (ACE) index is used to reflect the control-area power balance. The ACE signal includes interconnection frequency error and interchange power error with neighboring balancing authorities (BAs). It is used as an input to automatic generation control (AGC) systems (Wood, A. 1996 p.349). An AGC system automatically controls generation units, which participate in the regulation process. The regulation process is a real-time process and ACE is calculated every several seconds. Most BAs have their own AGC systems.

NERC Definition of ACE

The equation used by the North American Electric Reliability Corporation (NERC) to calculate ACE is:

$$ACE_{NERC} = (NI_A - NI_S) - 10\,B_i(F_A - F_S) - T_{0b} + I_{ME} \tag{1}$$

where NI_A = actual net interchange (MW),

NI_S = scheduled net interchange (MW),

B_i = frequency bias for the balancing authority's area (MW/0.1 Hz),

F_A = actual frequency (Hz),

F_S = scheduled frequency (normally 60 Hz),

T_{0b} = remaining bilateral payback for inadvertent interchange (MW),

I_{ME} = metering error correction (MW).

Each BA is required to keep its ACE within certain statistical limits established by the NERC Control Performance Standards (CPS) (Jaleeli, N. 1999 p.1092-1099). ACE is calculated independently for each BA, and the AGCs are operated accordingly to reduce ACEs of individual BAs.

WECC Differences

In the Western Electricity Coordinating Council (WECC) ACE expression, a term reflecting automatic time error correction is added:

$$ACE_{WECC} = (NI_A - NI_S) - 10B_i(F_A - F_S) - T_{0b} + I_{ME} + \frac{II_{primary}^{on/off\ peak}}{(1-Y)H} \tag{2}$$

where $Y = B_i / B_S$,

B_S = WECC system frequency bias (MW / 0.1 Hz),

$II_{primary}^{on/off\ peak}$ = the BA's accumulated primary inadvertent interchange (MWh); accumulation is calculated separately for on-peak and off-peak hours;

H = the number of hours used to payback inadvertent interchange energy.

Details and mathematical models of the WECC automatic time-error correction term are given in (Cohn, N. 1982 p.1144-1151 and Cohn, N. 1982 p.1152-1169).

Control Performance Standards

To evaluate the success of a balancing process, control performance standards are used. Control performance standards are introduced by NERC. There are two standards, CPS1 and CPS2, currently in place (Jaleeli, N. 1999 p. 1092-1099 and NERC 2007).

CPS1 assesses the impact of individual ACEs on interconnection frequency variations over a 12-month sliding window using one-minute average compliance factors. CPS2 is a monthly measure that a BA must report to NERC; it is calculated by averaging the ACE for each 10-minute period within a month. CPS2 is the percentage calculated by dividing the number of averages that are less than the BA's CPS2 limit by the total number of averages. A monthly CPS2 score of 90% or more is considered acceptable.

CPS1

Each BA shall achieve, as a minimum, CPS1 compliance of 100%. CPS1 is calculated as follows (NERC 2007):

$$CPS1 = (2 - CF) \cdot 100\% > 100\%, \tag{3}$$

where CF is a compliance factor calculated as:

$$CF = AVG_{12month}\left[CF_1\right] \tag{4}$$

$$CF_1 = \left[\left(\frac{ACE}{-10B} \right)_1 \left(\frac{\Delta F}{\varepsilon_1^2} \right)_1 \right] \tag{5}$$

where: ε_1 is the targeted frequency bound for CPS1 (Hz),.

ΔF is the interconnection frequency error (Hz),

B is the frequency bias of the control area, MW/0.1 Hz,

subscript 1 denotes the clock one-minute average.

CPS2

Each BA shall operate such that its average ACE is within a specific limit, (referred to as L_{10}) for at least 90% of clock ten-minute periods during a calendar month.

$$AVG_{10-\min}\left(ACE_i\right) \le L_{10} \tag{6}$$

$$L_{10} = 1.65\varepsilon_{10}\sqrt{(-10B_i)(-10B_s)} \tag{7}$$

$$CPS2 = \left[1 - \frac{violations_{month}}{total\ periods - unavailable\ periods} \right] \times 100\% > 90\% \tag{8}$$

where

ε_{10} is the targeted frequency bound (Hz).

B_i and B_s are the frequency bias settings of balancing authority i and the interconnection, respectively.

Balancing Authorities ACE Limit

The balancing authority ACE limit (BAAL) standard is a part of a new set of control performance standards currently under trial use in the industry (WECC 2006). BAAL is designed to replace CPS2. It establishes frequency-dependent ACE limits.

"The standard has been designed so that the BA ACE limits become frequency sensitive and can be used by the system operators as performance indicators in real time. The balancing authority can monitor its own performance against its BAAL target and take corrective actions before one of its BAAL limits is exceeded." (WECC 2006)

The following important considerations outlining potential impacts of the BAAL standard on system operations can be foreseen at present:

- A control that opposes frequency deviation always improves area performance against the BAAL. This means that the new standard will not have potential problems with compliance if control of the regulating resources is based on the local frequency signals rather than AGC signals.

- Distributed resources that react to local frequency signals will contribute to BAAL compliance without being connected to the BA control signal. This would dramatically increase opportunities for distributed resources' demand-side control and decrease associated costs (as a result of eliminating telemetry systems connecting the AGC system with distributed resources and loads).
- BAAL is designed to replace the CPS2 standard; therefore, no controversy is expected from interaction of local frequency-based controls with the CPS2 requirements.
- Unlike the CPS2 standard formulated for 10-minute averages of ACE, the BAAL standard is formulated for instantaneous values of the area control error.
- The BAAL standard is expected to relax the area regulation needs and reduce the regulation burden on resources providing regulation service.

BAAL limits depend on current frequency *f* and can be calculated using the following equation:

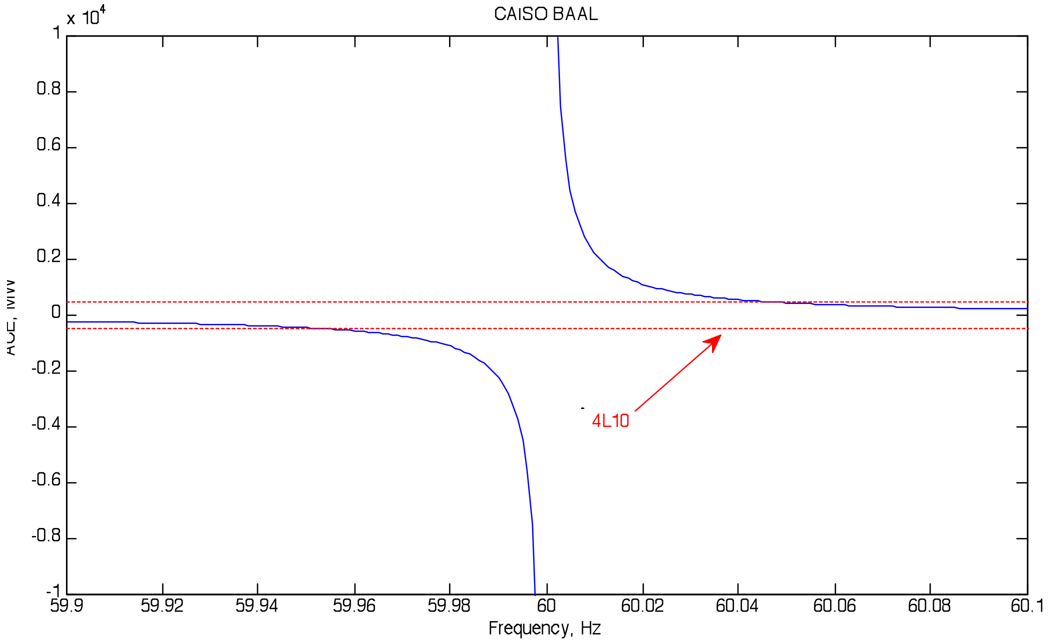
$$BAAL(f) = -10B\frac{(f_{low}-60)^2}{(f-60)} \tag{9}$$

where B is a BA frequency bias (MW/0.1 Hz). For example, the CAISO's frequency bias is −485 MW/0.1 Hz

f_{low} is a low frequency trigger limit (Hz). For the Western Interconnect, f_{low} = 59.932 Hz;

Figure 6 illustrates CAISO BAALs calculated using (9). $4L_{10}$ limits are also shown. The $4L_{10}$ limits are temporarily used to restrict BA interchange variations; this measure is a precaution taken before sufficient experience is gained with BAAL, or a more justified additional limit is applied to the BA's ACE.

Figure 6 CAISO's BAAL and $4L_{10}$ Limits



Goals of This Project

The objective of this project is to develop a tool to estimate CAISO's needed procurement of upward and downward regulation reserve in terms of its capacity, ramp rate and ramp duration for each operating hour of the next day. Based on a scientific approach that uses a pre-specified level of confidence, the estimate will minimize the procurement requirements without compromising reliability and compliance with mandatory control performance standards.

Report Organization

The report is organized as follows. Chapter 2 provides a description of the methodologies and simulation scenarios of this study. Chapter 3 discusses a software tool developed to implement the methodology. Chapter 4 presents the results of an empirical analysis performed to predict regulation requirements. Finally, Chapter 5 provides recommendations and concludes the report.

Appendices are also included that provide additional information on the ramping analysis methodology; a separate technical appendix provides the database specification description.

CHAPTER 2:
Estimation Methodologies for Developed Regulation Requirements

The predicted hourly regulation requirements for the next day are determined through a statistical analysis of retrospective information.

A moving window is applied to historical operational data to collect sufficient statistical information. The day-ahead hourly regulation requirements are determined based on a pre-specified confidence level.

Method I: Statistical Analysis of Real-Time Forecast and Dispatch Errors

The first method uses a statistical analysis of real-time forecast and dispatch errors that affect the CAISO ACE signal to predict day-ahead regulation requirements. The components of the ACE equation are used to calculate one-minute-resolution ideal-regulation curve that would correspond to zero ACE. This curve consists of the summation of the ACE components listed below as shown in Figure 7.

According to (1), a balancing authority ACE includes interchange error component ΔI, frequency error component $10B\Delta f$, metering-error correction component I_{ME}, automatic time-error correction component I_{TE}, and inadvertent interchange payback component T_{0b}.

Interchange error can be calculated using the equation

$$\Delta I = NI_A - NI_S \tag{10}$$

where $NI_A = G_A + W_A + S_A - L_A$,

$NI_S = G_S + W_S + S_S - L_S$,

G_A is the actual conventional generation (without wind and solar),

W_A is the actual wind generation,

S_A is the actual solar generation,

L_A is the actual load,

G_S is the generation dispatch (schedule),

W_S is the wind generation forecast (schedule),

S_S is the solar generation forecast (schedule), and

L_S is the load forecast (schedule).

Thus, the interchange error can be defined as:

$$\Delta I = (G_A + W_A + S_A - L_A) - (G_S + W_S + S_S - L_S) = \Delta G + \Delta W + \Delta S - \Delta L \tag{11}$$

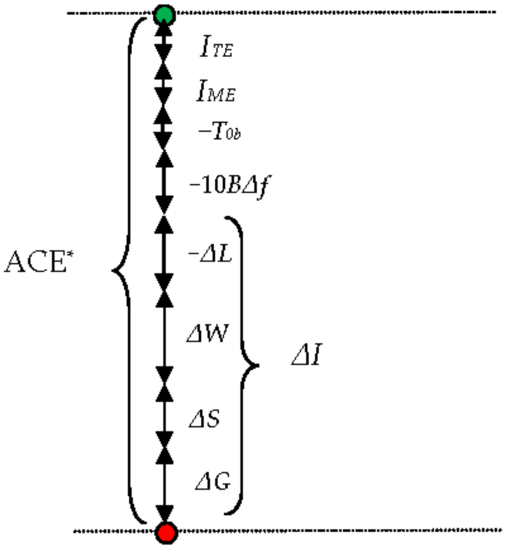
where ΔG is the uninstructed deviation of conventional generation units,

ΔW is the wind generation forecast error,

ΔS is the solar generation forecast error, and

ΔL is the load forecast error.

Figure 7. Calculated Ideal Regulation Used in Method I



If a BA does not have regulation, its ACE would be as follows:

$$ACE^* = \Delta G + \Delta W + \Delta S - \Delta L - 10B\Delta f - T_{0b} + I_{ME} + I_{TE} \tag{12}$$

Assuming that the BA's goal is to keep its ACE as close as possible to zero, the ideal regulation requirement would be:

$$REG^* = -ACE^* \tag{13}$$

Figure 8 presents CAISO real-time load, wind and solar forecast errors, frequency error, uninstructed deviation, and automatic time error correction values observed in certain hours of 2010. These components are used in (12) and (13) to calculate regulation requirements presented in Figure 9.

Figure 8. Regulation Requirements Components (Method I) (CAISO, 12/4/2010)

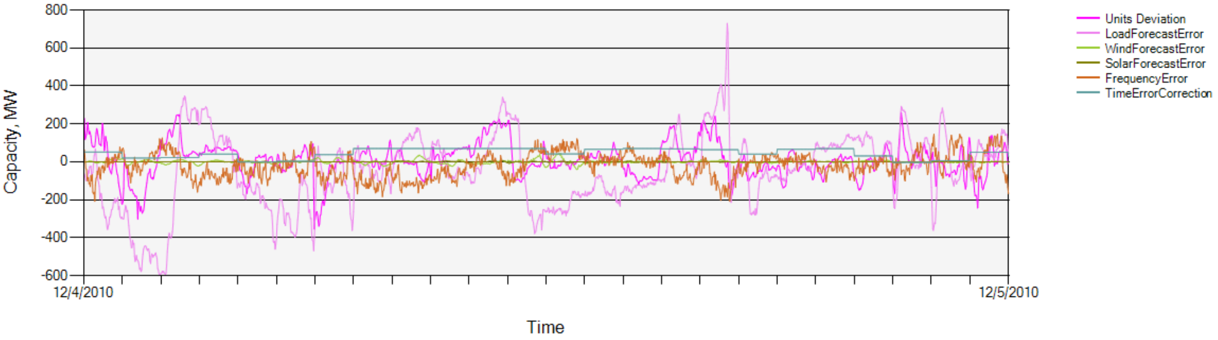
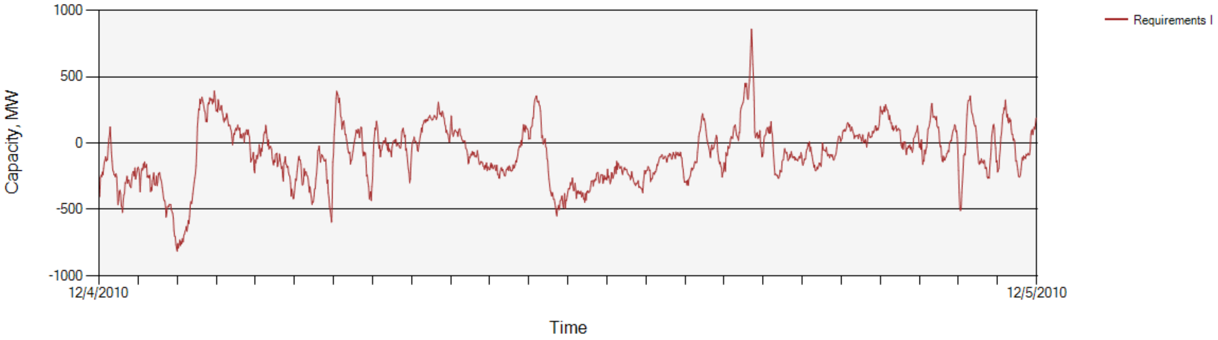


Figure 9. Ideal Regulation Requirements (REG*) Calculated by Method I (CAISO, 12/4/2010)



Method II: Statistical Analysis of Actual ACE and Regulation Data

Method II estimates regulation requirements by perforoming a statistical analysis of the actual CAISO ACE signal and the actual CAISO regulation data (Makarov, Y.V. 2009 p.1039-1050).

Ideal Regulation Requirements

A minute-by-minute ideal-regulation curve is obtained by subtracting the actual ACE from the actual regulation values as shown in Figure 10.

$$REG^* = -ACE^* = REG_A - ACE_{WECC}, \tag{14}$$

where ACE^* is the ACE that would be observed in the case of no regulation in the BA control area, REG_A is the actual regulation applied to the system, and ACE_{WECC} is the BA ACE defined in (2).

This REG^* curve represents the ideal regulation needed to have a zero ACE.

Figure 10. Calculated Ideal Regulation Used in Method II

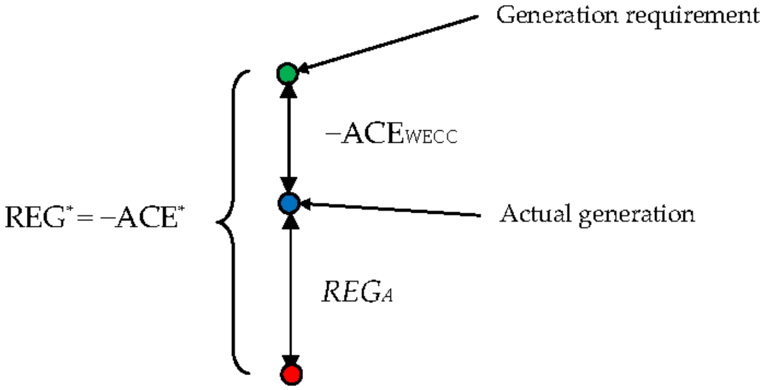


Figure 12 presents CAISO's ACE and the actual regulation-applied values observed on 12/4/2010. These components are used in (14) to calculate the regulation requirements presented in Figure 13.

Figure 12. Regulation Requirement Components (Method II) (CAISO, 12/4/2010)

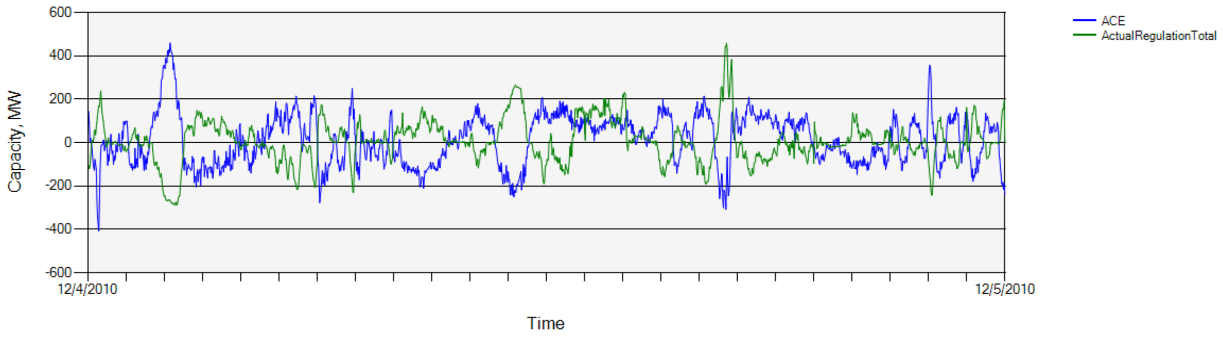
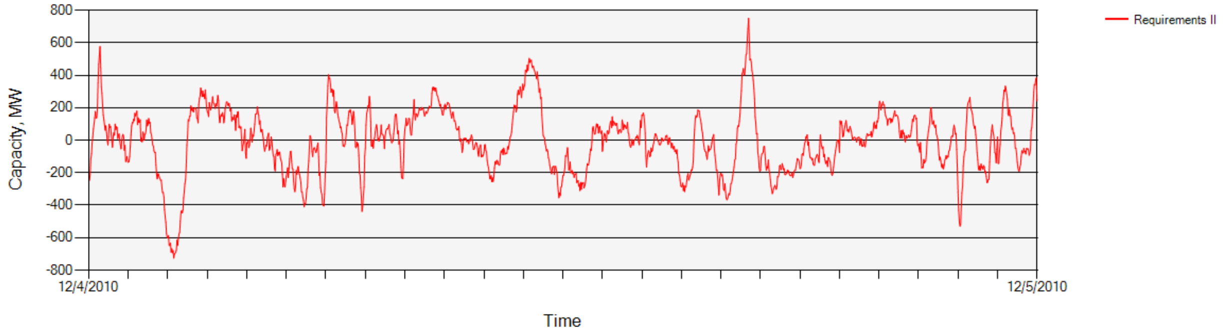


Figure 13. Regulation Requirements (REG*) Calculated by Method II (CAISO, 12/4/2010)



CPS2 Compliance

Equation (14) for the ideal regulation value overestimates the needed regulation because it drives the ACE value to zero. This target is neither economical nor practically achievable. A more realistic regulation value can be calculated based on the required compliance level with the CPS2 requirements. There are multiple possible ways to reduce the regulation reserve capacity from the level required by ideal regulation service to the level needed to meet CPS2 requirements or any other level desired by the system operator. In this project, we adapted an approach in which the ACE signal is reduced by a value proportional to a BA's L_{10}. The system operator can specify an experimental proportionality coefficient to help reach the desired level of CPS2 compliance.

In this approach, a new term taking into account the L_{10} limit can be introduced into Equation (14) to calculate regulation requirements REG^{**} as follows:

$$REG^{**} = \begin{cases} -ACE^{*} + \alpha L_{10}, \, if \;\; ACE^{*} > L_{10} \\ -ACE^{*} - \alpha L_{10}, \, if \;\; ACE^{*} < -L_{10} \\ -ACE^{*}, \, if \; -L_{10} < ACE^{*} < L_{10} \end{cases} , \tag{15}$$

where the coefficient α can be determined based on the CAISO's CPS2 compliance level target.

Method III: Calculation of Regulation Requirements Based on BAAL Compliance

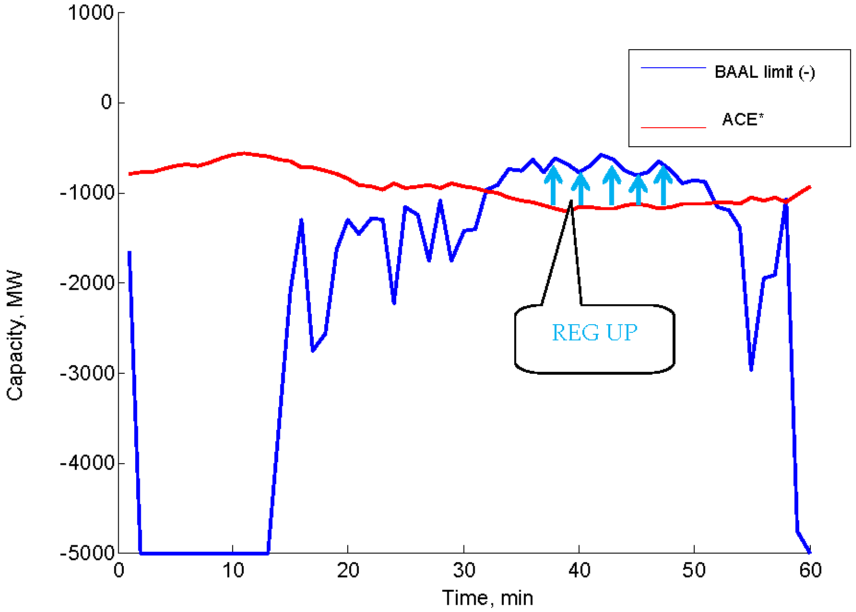
To meet the BAAL standard requirements, the ACE signal at time *t* should satisfy the constraint

$$BAAL_{\min t} < ACE_{t}^{*} < BAAL_{\max t}, \tag{16}$$

where $BAAL_{\max t}$ and $BAAL_{\min t}$ are limits at time *t* calculated using (9); ACE_{t}^{*} is a BA's ACE in the case that the system does not have regulation at time *t* and is calculated using (14). According to the BAAL standard, the ACE signal is allowed to be outside BAAL limits for a certain time (up to 30 minutes). A methodology for incorporating the timing component into regulation requirements calculation will be given in the next section.

Figure 14 illustrates the proposed methodology for identifying regulation needed to meet the BAAL standard requirements. The blue curve represents the CAISO's BAAL limit and the red curve represents CAISO's ACE*. One can see a violation of the BAAL limit from approximately minute 30 to minute 50. To address this violation, a regulation-up control action should be applied (shown as blue arrows) to keep ACE within the limits.

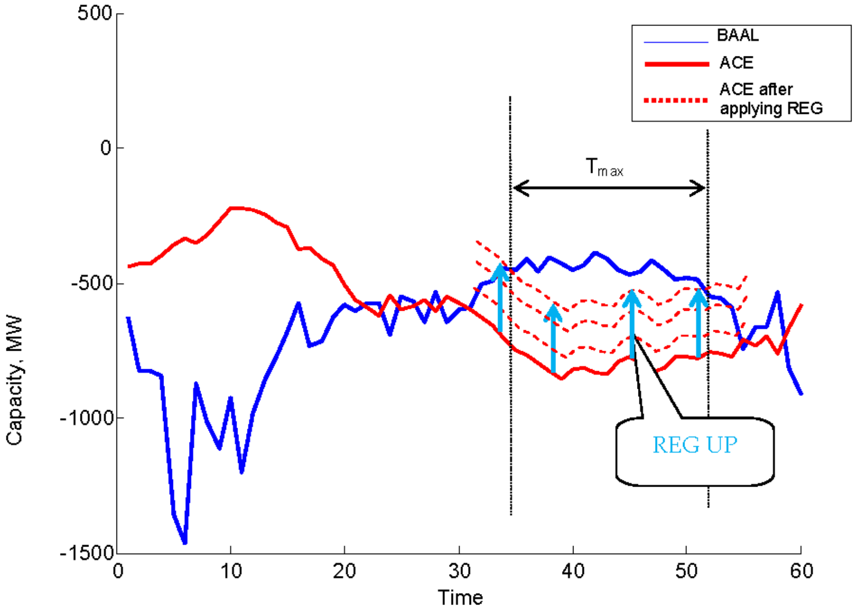
Figure 14. ACE* vs. BAAL Limit (CAISO, 07/18/10 from 11:00 to 12:00)



Timing Component

For each violation, the BAAL standard allows a BA to have its ACE outside BAAL limits for a certain time (up to 30 minutes). To reflect this flexibility, an additional timing component can be added to the methodology for estimating the regulation need (as shown in Figure 15). In this approach, a maximum allowed time T_{max} of having a BAAL limit violation can be specified from 0 to 30 minutes. In this figure, the red curve shows the ACE signal during one hour (from 0 to 60 minutes), while the blue curve shows the lower BAAL limits during the same period. When the ACE signal is below the BAAL lower limit for more than 30 minutes, the BA could be penalized for noncompliance. To avoid noncompliance, a time limit, $T_{max} < 30$ minutes is introduced, during which the system could go outside the BAAL limits. The regulation is only applied if the ACE signal is below the BAAL lower limit for a period longer than T_{max}. The regulation signal shifts the ACE curve along the capacity axis. This is illustrated in Figure 15, where the shifted ACE curve is shown as a family of dashed red lines. So as regulation up is applied (shown as light blue arrow), the ACE curve is shifted up (red dashed curve) so that ACE is not exceeding the BAAL lower limit for more than $T_{max.}$

Figure 15. Timing Component



Safety Margin

Additional safety margins ΔP_{margin} and Δf_{margin} can be used to support a more robust compliance with the BAAL standard. In this case, the BAAL compliance condition can be modified as follows.

$$BAAL_{\min t} < ACE_t^* + \Delta P_{margin} - 10B_i \cdot \Delta f_{margin} < BAAL_{\max t} \tag{17}$$

$$BAAL_{\max t} = -10B \frac{(f_{low} - 60)^2}{(f_t - 60) + \Delta f_{margin}}, if\ (f_t + \Delta f_{margin}) > 60 \tag{18}$$

$$BAAL_{\min t} = -10B \frac{(f_{low} - 60)^2}{(f_t - 60) + \Delta f_{margin}}, if\ (f_t + \Delta f_{margin}) < 60 \tag{19}$$

where ΔP_{margin} reflects the size of contingences (for generation trip the value is negative; for load drop the value is positive) *and* Δf_{margin} is a frequency deviation caused by a contingency

$$\Delta f_{margin} = \frac{\Delta P_{margin}}{-10B_S} \tag{20}$$

where $B_S = -2088$ MW/0.1 Hz is the WECC system frequency bias.

An illustration of the generator tripping is shown in Figure 16. Loss of a generator leads to a frequency drop (black curve) and an ACE excursion (red curve). At the same time a value of lower limit $\text{BAAL}_{\min}$ (blue curve) is decreased because the BAAL limit is frequency dependent. To prevent a potential BAAL limit violation, a regulation-up control action should be applied (as shown by green arrows) that keeps ACE within the limits (Figure 16).

Figure 16. Responses to a Generation Trip

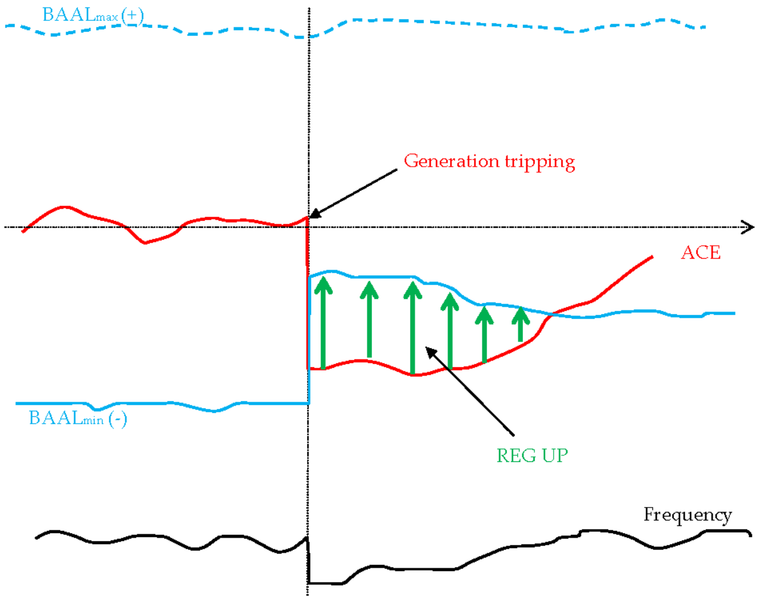
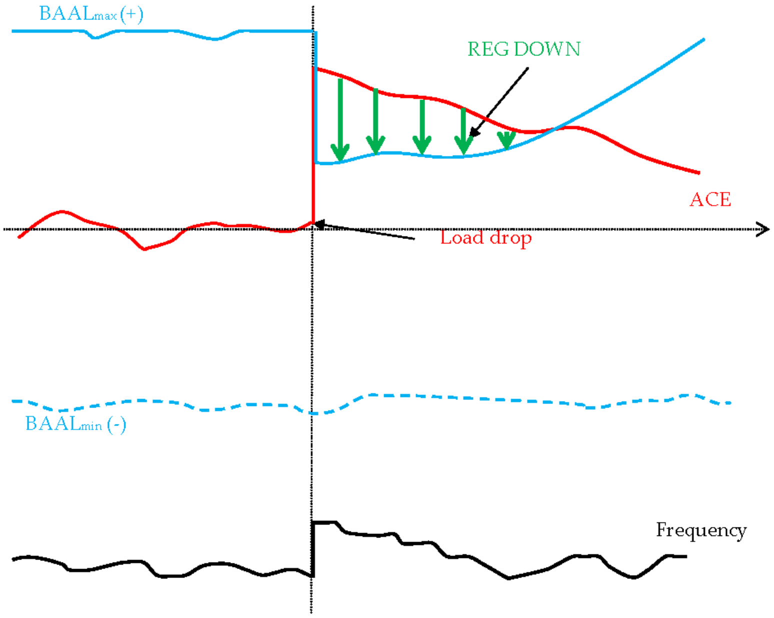


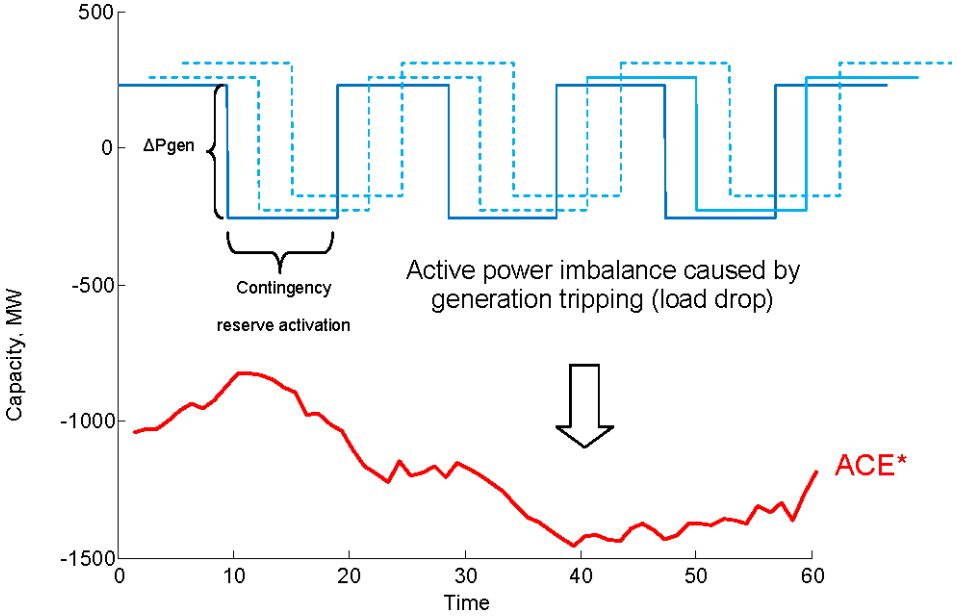
Figure 17 illustrates a load-drop event. In this case a regulation-down control action is needed.

Figure 17. Responses to a Load Drop



To reflect the potential impact of generator trips and load drops on compliance with the BAAL standard, the user can optionally apply additional disturbance sequences to the BA's ACE* as shown in Figure 18. Disturbances include generation-trip and load-drop events. Duration of the disturbances can be made equal to the contingency-reserve activation time (10 min). The sizes (capacities) of the disturbances can be made equal to the capacity of the largest generation unit and largest load in the BA's operational jurisdiction. After applying the additional disturbance signal, the regulation control action is identified on a level sufficient to meet the BAAL standard requirements.

Figure 18. Implementing a Safety Margin



Additional Constraints

The user can opt to add a number of additional constraints to help address different aspects of grid balance control.

1. The $4L_{10}$ constraint is added by CAISO to limit the impact of large ACE variations on the control area interchange. The $4L_{10}$ limit is applied the same way as the BAAL limit. ACE* at time *t* must be within ± $4L_{10}$ limits:

$$-4L_{10} < ACE_t^* < 4L_{10} \tag{21}$$

2. Frequency constraints reflect the instantaneous frequency limits established by the new NERC standards, that is the frequency abnormal limit, the frequency trigger limit, and the frequency relay limit (NERC 2011).

$$f_{\min} < f_{sched} + \Delta f_t < f_{\max} \tag{22}$$

3. The interchange deviation constraint forces the BA interchange to stay within a predefined limit, so that significant deviations are suppressed by AGC control.

$$\Delta I_{\min} < \Delta I_t < \Delta I_{\max} \tag{23}$$

If the operating point at time *t* satisfies constraints (16) and (21) – (23) then the regulation requirement at point *t* is equal to zero.

$$REG_t^{**} = 0 \tag{24}$$

If one or more constraints are violated at point *t*, then the regulation requirements can be calculated using the following equation:

$$REG_t^{**} = k_{AGC} \cdot \Delta_t \,, \tag{25}$$

where k_{AGC} is a coefficient reflecting the AGC system performance, i.e., the additional regulation requirement appearing because of the non-ideal nature of units providing regulation service.

$$\begin{aligned} \Delta_t &= \Delta_{t+}, if \left|\Delta_{t+}\right| > \left|\Delta_{t-}\right| \\ \Delta_t &= \Delta_{t-}, if \left|\Delta_{t+}\right| < \left|\Delta_{t-}\right| \end{aligned} \tag{26}$$

where

$$\begin{aligned} \Delta_{t+} &= \max\left\{\Delta_{BAAL}, \Delta_{L10}, \Delta_f, \Delta_{\Delta I}\right\} \\ \Delta_{t-} &= \min\left\{\Delta_{BAAL}, \Delta_{L10}, \Delta_f, \Delta_{\Delta I}\right\} \end{aligned} \tag{27}$$

$$\Delta_{BAAL} = \begin{cases} BAAL_{\max} - ACE_t^*, if\ ACE_t^* > BAAL_{\max} \\ BAAL_{\min} - ACE_t^*, if\ ACE_t^* < BAAL_{\min} \end{cases} \,, \tag{28}$$

$$\Delta_{L10} = \begin{cases} 4L_{10} - ACE_t^*, if\ ACE_t^* > 4L_{10} \\ -4L_{10} - ACE_t^*, if\ ACE_t^* < -4L_{10} \end{cases} \tag{29}$$

$$\Delta_f = \begin{cases} -10B\left(f_{\max} - (f_{sched} + \Delta f_t)\right), if\ (f_{sched} + \Delta f_t) > f_{\max} \\ -10B\left(f_{\min} - (f_{sched} + \Delta f_t)\right), if\ (f_{sched} + \Delta f_t) < f_{\min} \end{cases} \tag{30}$$

$$\Delta_{\Delta I} = \begin{cases} \Delta I_{\max} - \Delta I_t, if\ \Delta I_t > \Delta I_{\max} \\ \Delta I_{\min} - \Delta I_t, if\ \Delta I_t < \Delta I_{\min} \end{cases} \tag{31}$$

Proposed Statistical Analysis Approach

Stage 1: Data Acquisition

In order to model the statistical uncertainty characteristics, large volumes of historical data are needed. A sliding window is used for acquiring statistical information on load, wind and solar power generation forecast and their actually observed values, as well as ACE and actual regulation applied to the system. Table 2 lists all the data needed for the uncertainty evaluation in Methods I, II and III.

Table 2. Data Specification

Data	Data Units	Data Resolution
Method I		

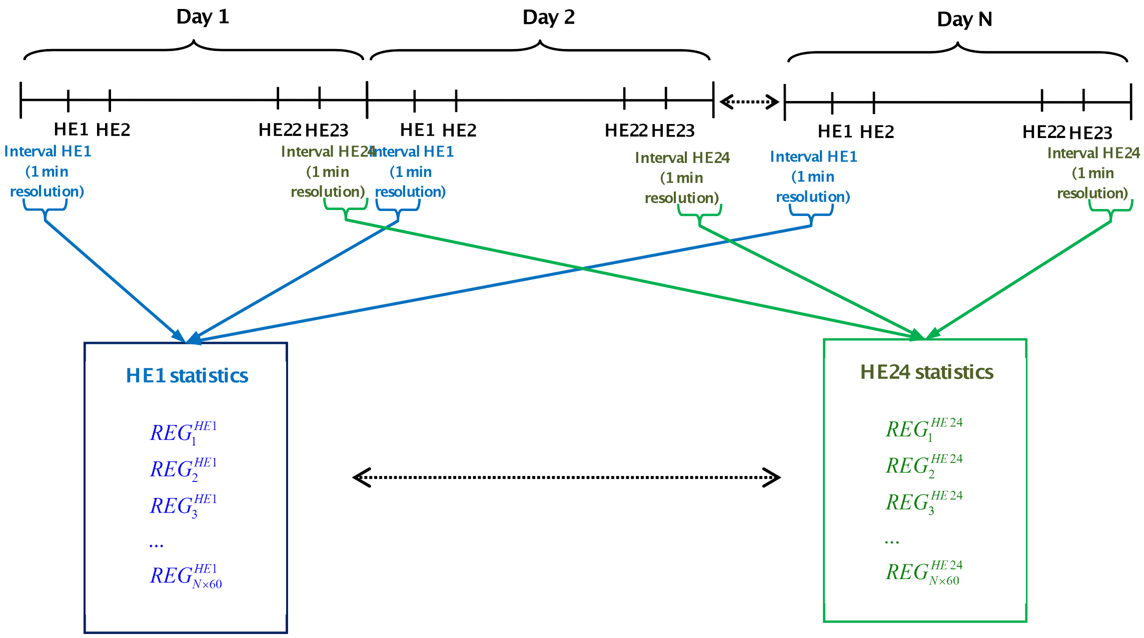
Total Uninstructed Deviation of Conventional Generators	MW	1 minute
Actual Load	MW	1 minute
Real-time Load Forecast	MW	5 minute
Actual Wind Generation	MW	1 minute
Real-time Wind Generation Forecast	MW	5 minute
Actual Solar Generation	MW	1 minute
Real-time Solar Generation Forecast	MW	5 minute
Actual Frequency	Hz	1 minute
Scheduled Frequency	Hz	1 minute
Frequency Bias Setting	MW/0.1 Hz	-
Automatic Time Error Correction	MW	1 minute
Method II & III		
Raw ACE	MW	1 minute
Actual Applied Regulation Up	MW	1 minute
Actual Applied Regulation Down	MW	1 minute

Retrospective information on regulation requirements is calculated using (12) for Method I, (14) for Method II, and (25) for Method III.

Stage 2: Statistical Analysis

The next stage includes a statistical analysis of the retrospective information acquired in the first stage. The analysis is performed separately for each operating hour of a day (from hour ending (HE) 1 to HE 24) as shown in Figure 19. Capacity requirements are calculated using a time-varying empirical probability density function (PDF). The description of this method is given below. Analysis of ramping requirements is based on the swinging-door algorithm (see APPENDIX A for details).

Figure 19. Regulation Requirements Calculation

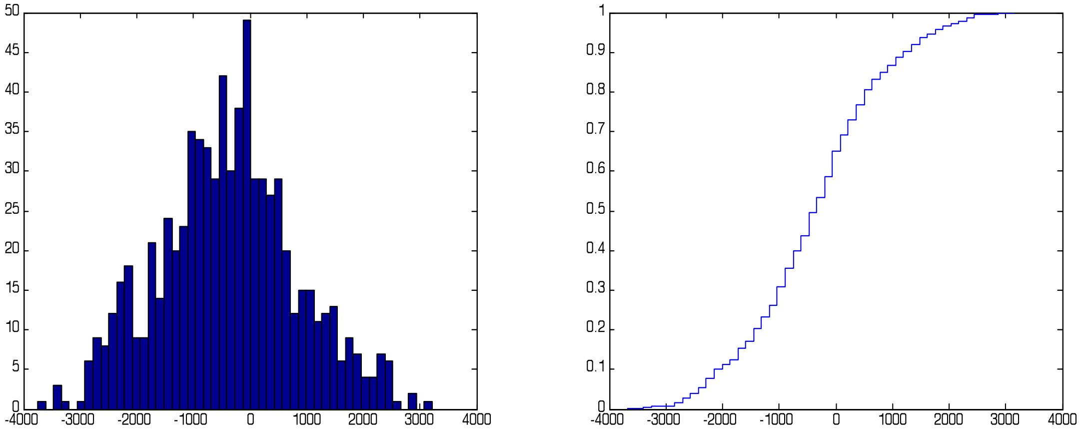


Empirical Probability Approach

When data do not follow any standard probability distribution, so-called nonparametric models become more appropriate. These models are based on empirical probability distributions and make no assumptions about the form of the underlying distribution, so no parameter estimates are needed (Makarov, Y. 2010).

The idea behind building the empirical cumulative distribution function (CDF) is relatively simple. The CDF is a function that assigns probability $1/n$ to each of n observations of the analyzed parameter. The CDF value for any specific parameter's value is calculated by adding all probabilities for samples with smaller values of the parameter. Its graph has a stair-step appearance. If a sample comes from a parametric distribution (such as a normal distribution), its empirical CDF will resemble the CDF of the parametric distribution. If not, the empirical distribution still approximates the CDF for the non-parametric distribution (Makarov, Y. 2010). Examples of empirical distributions (net load-forecast error distribution and its empirical CDF) are presented in Figure 20.

**Figure 20. Day-Ahead Net Load-Forecast Error Distribution (CAISO Data, June-August, 2007):
a) Histogram; b) Empirical CDF**



a b

Stage 3: Evaluation of Regulation Requirements

At the next stage, an evaluation of day-ahead regulation requirements with a specified level of confidence is performed. The evaluation is based on statistical characteristics of the regulation requirement obtained in the previous stages.

The proposed statistical approach, based on the time-varying empirical probability density function, is used in the study to determine the uncertainty ranges of the regulation requirement.

The uncertainty range defines an interval within which a random parameter is expected to be found with a specified level of confidence. To determine an uncertainty range, it is sufficient to find two solutions of the inverse CDF corresponding to the desired percentiles on both ends of the distribution. The inverse CDF is defined as follows (MathWorks 2010):

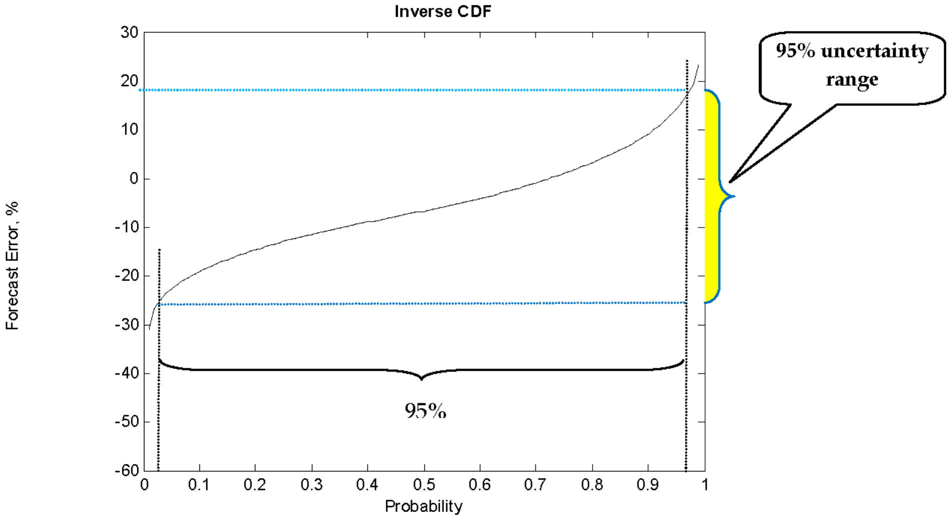
If the CDF is continuous, the inverse CDF function $CDF^{-1}(p),\ p\in[0,1]$ defines real numbers x such that $CDF(x) = p$. The inverse of the CDF is called the quantile function. An evaluation of the quantile function often involves special numerical methods.

Our task is to find the forecast error range $x_1 \ldots x_2$ to the given level of confidence p

$$CDF(x_2) - CDF(x_1) = p(x_1 \le X \le x_2) = \int_{x_1}^{x_2} PDF(x)\,dx \tag{32}$$

The inverse CDF function for the net load-forecast error is presented in Figure 21. The uncertainty range is evaluated at a 95% confidence level, which corresponds to the 2.5 to 97.5 percentiles of the distribution.

Figure 21. An Example of Net Load-Forecast Error Inverse CDF Function and Corresponding 95% Uncertainty Range



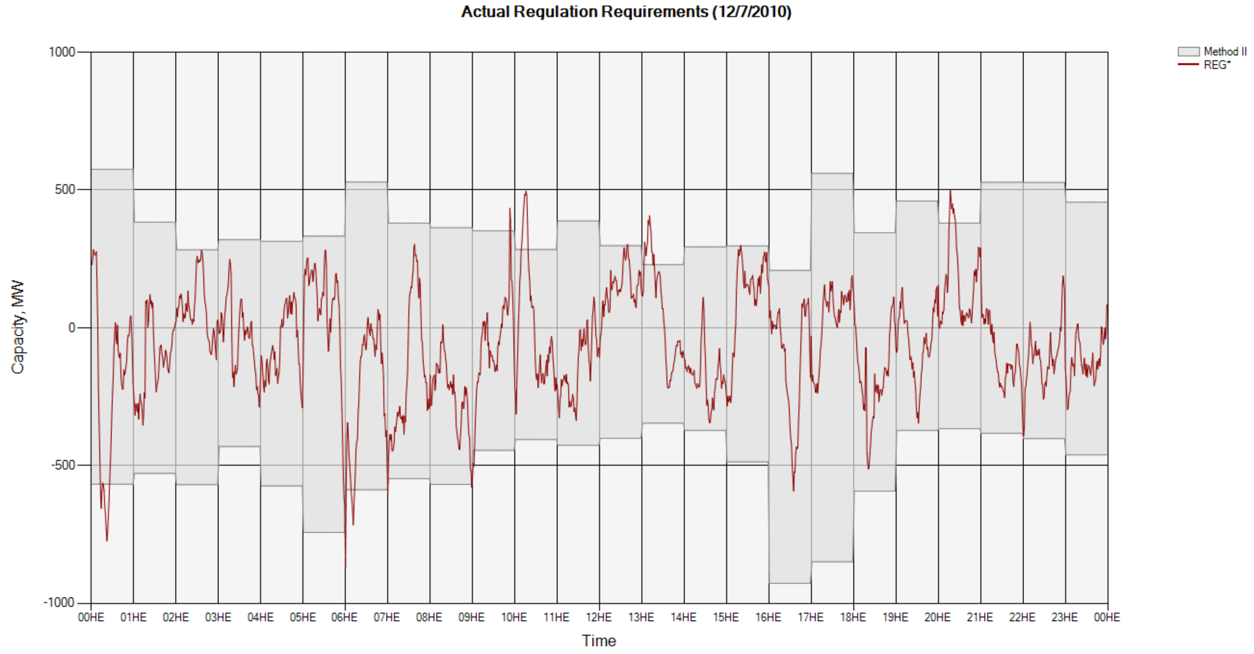
Self-Validation Approach

A validation approach based on comparing the predicted uncertainty ranges against the actually observed ranges has been developed and applied to validate the accuracy of the model.

The validation approach includes the following calculations: (1) Count the actual points found within the predicted uncertainty ranges, and calculate the corresponding percentages. (2) Compare the obtained actual percentages with the target percentages corresponding to the confidence level of the interval. The uncertainty algorithm would be validated if the calculated actual percentages and the target percentages are close.

Figure 22 shows actual regulation requirements observed on 12/7/2010 (dark red curve) and a regulation requirements prediction with 95% level of confidence (gray range). One-minute resolution is used, which means a total of 1440 data points per day. In the example, 1382 actual points (96%) are within the predicted range (Figure 22). The target percentage corresponds to the confidence level of the range – 95%. Thus the calculated (observed) percentage is very close to the targeted percentage.

Figure 22. Actual Regulation Requirements vs. 95% Confidence Level Regulation Requirements Prediction (12/7/2010)



Real-Time Forecast Errors

Wind and Solar Generation Forecast Errors

Currently, the real-time wind and solar generation forecast is not provided or included into the CAISO real-time dispatch process. Instead, the naïve persistence model is implicitly used (Figure 23). Practically this means that, for example, for a 5-minute dispatch interval [t + 5, t + 10], the implicit real-time wind (or solar) generation forecast is assumed to be equal to the average actual wind (or solar) generation at the moment [t – 5, t]

Figure 24 and Figure 25 show CAISO’s real-time wind and solar generation forecast errors for 12/9/2010 – 12/12/2010 calculated using the persistence model.

Figure 23. Naïve Persistence Model Illustration

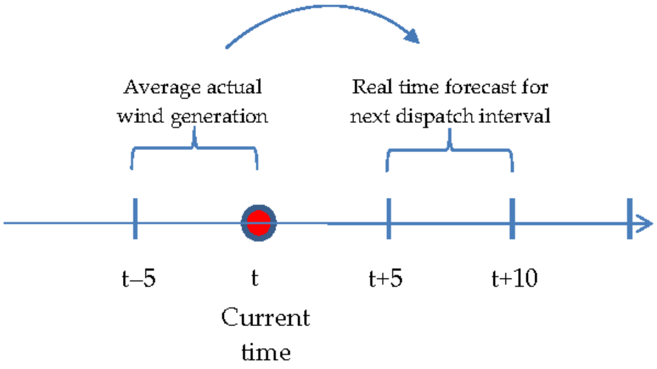


Figure 24. Real-Time Wind Generation Forecast (CAISO 12/9/2010 – 12/12/2010)

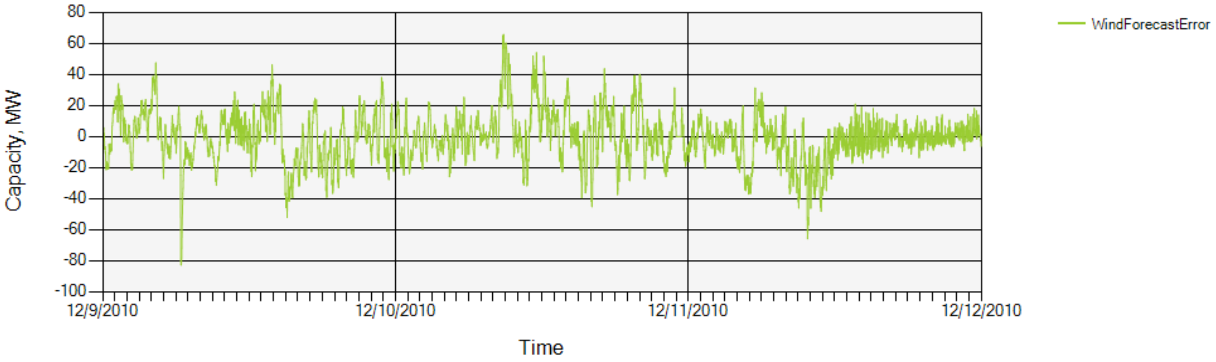
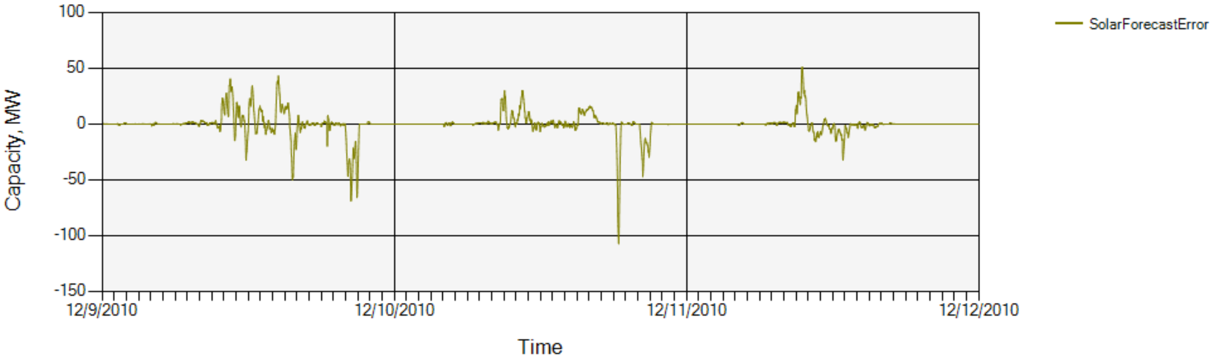


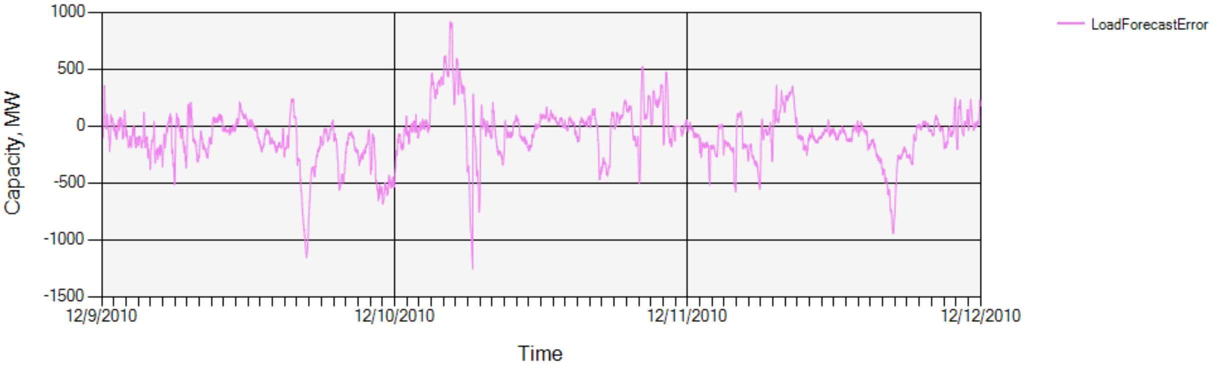
Figure 25. Real-Time Solar Generation Forecast (CAISO 12/9/2010 – 12/12/2010)



Load Forecast Errors

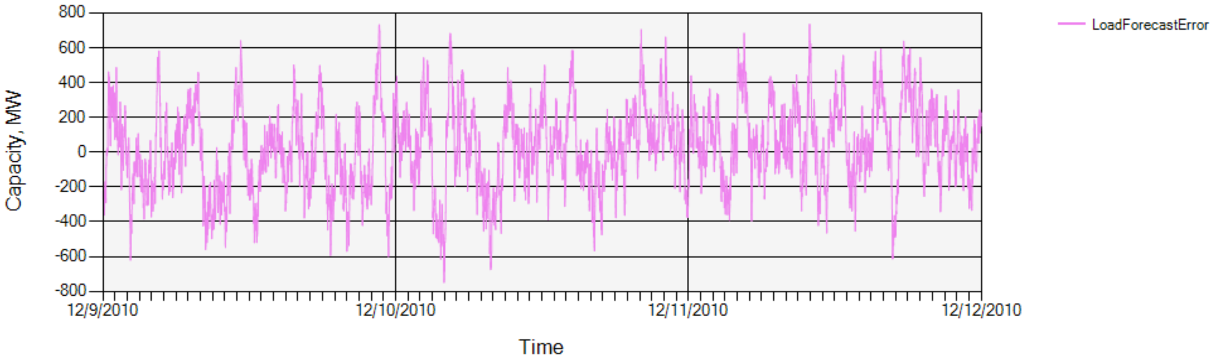
The observed real-time load forecast errors are used in Method I. Figure 26 presents the observed CAISO real-time load forecast errors on 12/9/2010 – 12/12/2010.

Figure 26. Real-Time Load Forecast Error (CAISO, 12/9/2010 – 12/12/2010)



During the Monte-Carlo simulation, the real-time load forecast errors are generated using a random-number generator based on the truncated normal distribution. Simulated load forecast errors (standard deviation $\sigma = 250$ MW) are presented in Figure 27.

Figure 27. Simulated Real-Time Load Forecast Error (Standard Deviation = 250 MW)



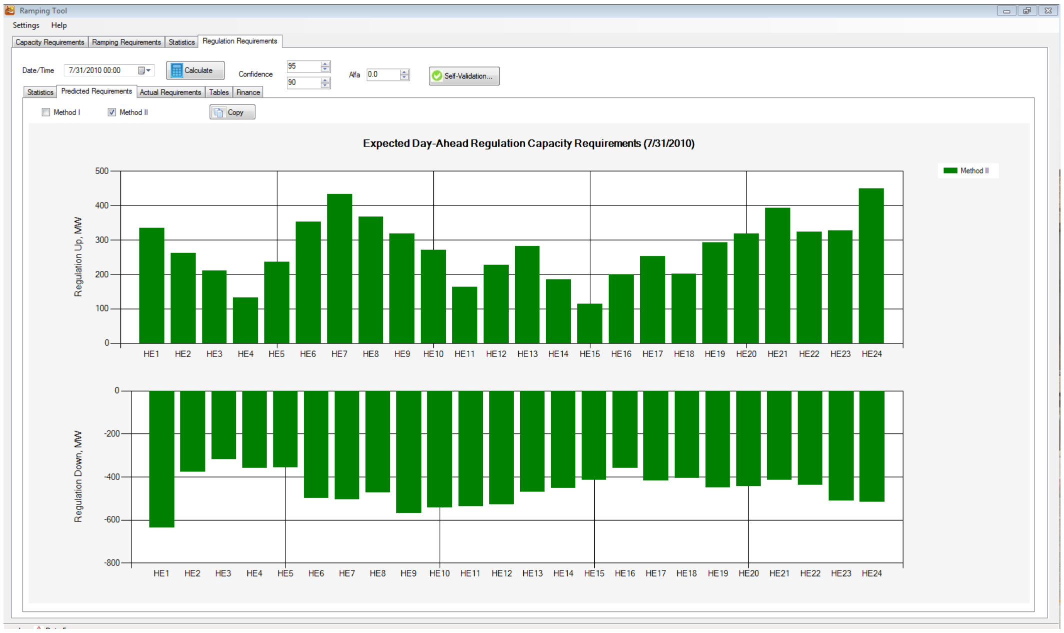
CHAPTER 3
Software Tool

A prototype regulation-requirements evaluation tool has been developed. The tool is based on the methodology developed in this project. The prototype has been installed at the CAISO control room for testing.

Prototype Design and User Interface

Microsoft Visual Studio® 2008 was used to develop the regulation prediction tool, which is deployed on the Microsoft Windows® platform and .NET Framework. The prototype consists of three main modules: the database, the uncertainty evaluation module and the display for results and alerts. The database is implemented in Oracle® 10g. The database specification is given in APPENDIX B. Examples of software user interface are presented in Figure 28 – Figure 31.

Figure 28. Screenshot of Day-Ahead Regulation Requirements Display



Date/Time 7/31/2010 00:00

Confidence 95 / 90

Alfa 0.0

☐ Method I

☑ Method II

Figure 27. Screenshot of Statistical Analysis Display

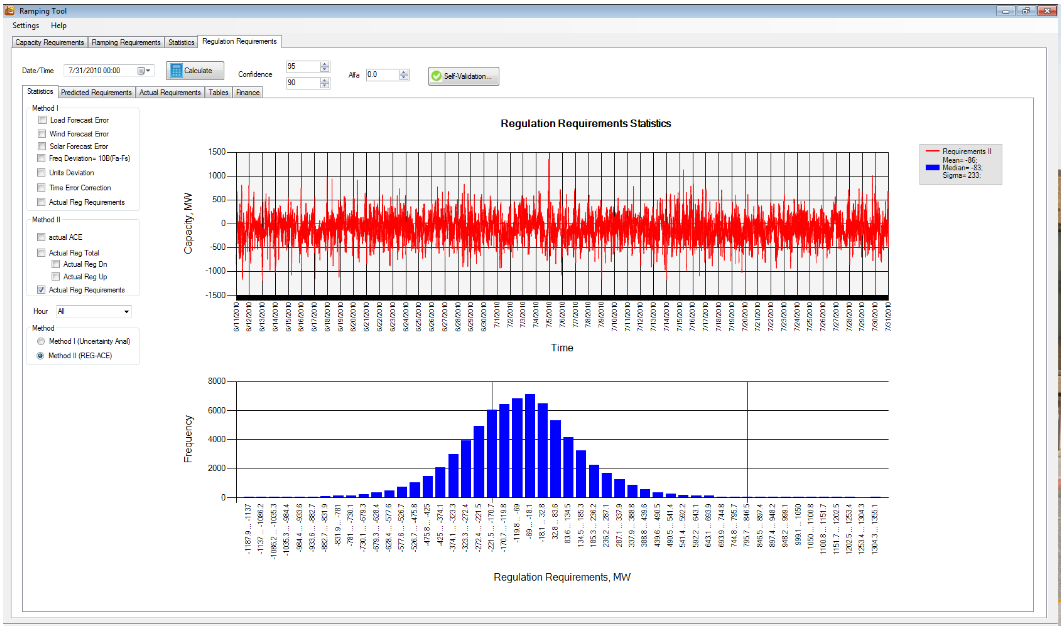


Figure 28. Screenshot of Actual Regulation Requirements Display

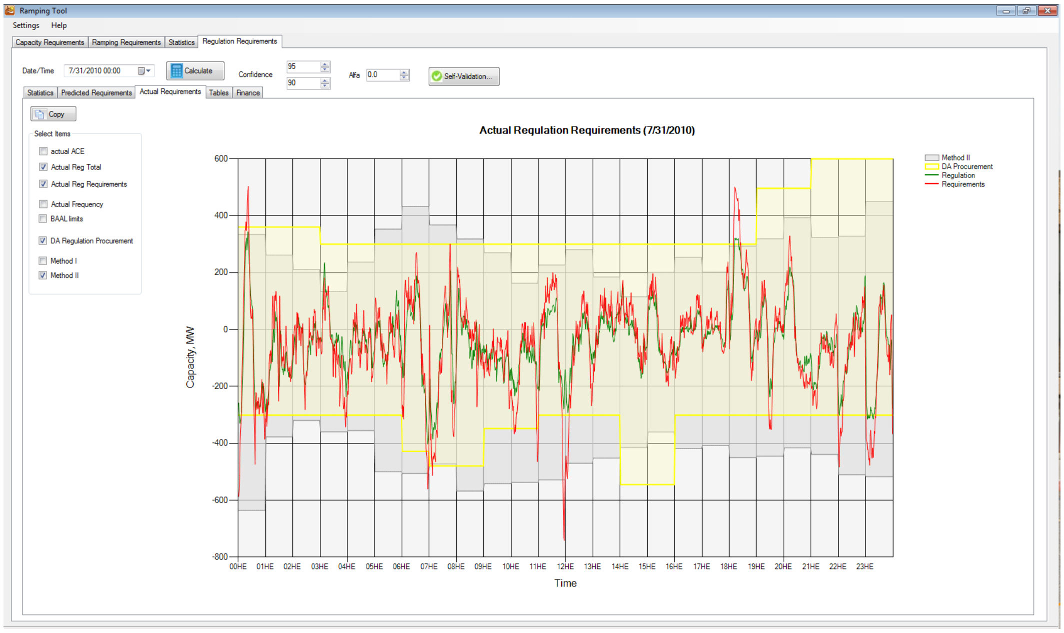
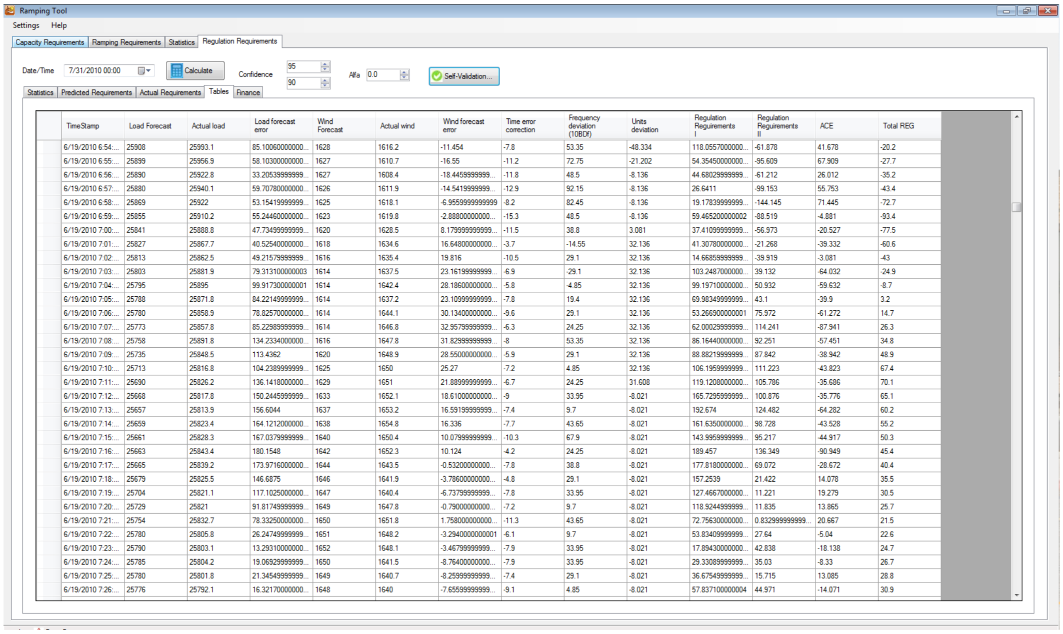


Figure 31. Screenshot of Database Display



Date/Time 7/31/2010 00:00

Confidence 95

90

Alfa 0.0

TimeStamp	Load Forecast	Actual load	Load forecast error	Wind Forecast	Actual wind	Wind forecast error	Time error correction	Frequency deviation (10BDf)	Units deviation	Regulation Reguirements I	Regulation Reguirements II	ACE	Total REG
6/19/2010 6:54:...	25908	25993.1	85.10060000000...	1628	1616.2	-11.454	-7.8	53.35	-48.334	118.0557000000...	-61.878	41.678	-20.2
6/19/2010 6:55:...	25899	25956.9	58.10300000000...	1627	1610.7	-16.55	-11.2	72.75	-21.202	54.35450000000...	-95.609	67.909	-27.7
6/19/2010 6:56:...	25890	25922.8	33.20539999999...	1627	1608.4	-18.4459999999...	-11.8	48.5	-8.136	44.68029999999...	-61.212	26.012	-35.2
6/19/2010 6:57:...	25880	25940.1	59.70780000000...	1626	1611.9	-14.5419999999...	-12.9	92.15	-8.136	26.6411	-99.153	55.753	-43.4
6/19/2010 6:58:...	25869	25922	53.15419999999...	1625	1618.1	-6.9559999999999	-8.2	82.45	-8.136	19.17839999999...	-144.145	71.445	-72.7
6/19/2010 6:59:...	25855	25910.2	55.24460000000...	1623	1619.8	-2.88800000000...	-15.3	48.5	-8.136	59.465200000002	-88.519	-4.881	-93.4
6/19/2010 7:00:...	25841	25888.8	47.73499999999...	1620	1628.5	8.17999999999...	-11.5	38.8	3.081	37.41099999999...	-56.973	-20.527	-77.5
6/19/2010 7:01:...	25827	25867.7	40.52540000000...	1618	1634.6	16.64800000000...	-3.7	-14.55	32.136	41.30780000000...	-21.268	-39.332	-60.6
6/19/2010 7:02:...	25813	25862.5	49.21579999999...	1616	1635.4	19.816	-10.5	29.1	32.136	14.66859999999...	-39.919	-3.081	-43
6/19/2010 7:03:...	25803	25881.9	79.313100000003	1614	1637.5	23.16199999999...	-6.9	-29.1	32.136	103.2487000000...	39.132	-64.032	-24.9
6/19/2010 7:04:...	25795	25895	99.917300000001	1614	1642.4	28.18600000000...	-5.8	-4.85	32.136	99.19710000000...	50.932	-59.632	-8.7
6/19/2010 7:05:...	25788	25871.8	84.22149999999...	1614	1637.2	23.10999999999...	-7.8	19.4	32.136	69.98349999999...	43.1	-39.9	3.2
6/19/2010 7:06:...	25780	25858.9	78.82570000000...	1614	1644.1	30.13400000000...	-9.6	29.1	32.136	53.266900000001	75.972	-61.272	14.7
6/19/2010 7:07:...	25773	25857.8	85.22989999999...	1614	1646.8	32.95799999999...	-6.3	24.25	32.136	62.00029999999...	114.241	-87.941	26.3
6/19/2010 7:08:...	25758	25891.8	134.2334000000...	1616	1647.8	31.82999999999...	-8	53.35	32.136	86.16440000000...	92.251	-57.451	34.8
6/19/2010 7:09:...	25735	25848.5	113.4362	1620	1648.9	28.55000000000...	-5.9	29.1	32.136	88.88219999999...	87.842	-38.942	48.9
6/19/2010 7:10:...	25713	25816.8	104.2389999999...	1625	1650	25.27	-7.2	4.85	32.136	106.1959999999...	111.223	-43.823	67.4
6/19/2010 7:11:...	25690	25826.2	136.1418000000...	1629	1651	21.88999999999...	-6.7	24.25	31.608	119.1208000000...	105.786	-35.686	70.1
6/19/2010 7:12:...	25668	25817.8	150.2445999999...	1633	1652.1	18.61000000000...	-9	33.95	-8.021	165.7295999999...	100.876	-35.776	65.1
6/19/2010 7:13:...	25657	25813.9	156.6044	1637	1653.2	16.59199999999...	-7.4	9.7	-8.021	192.674	124.482	-64.282	60.2
6/19/2010 7:14:...	25659	25823.4	164.1212000000...	1638	1654.8	16.336	-7.7	43.65	-8.021	161.6350000000...	98.728	-43.528	55.2
6/19/2010 7:15:...	25661	25828.3	167.0379999999...	1640	1650.4	10.07999999999...	-10.3	67.9	-8.021	143.9959999999...	95.217	-44.917	50.3
6/19/2010 7:16:...	25663	25843.4	180.1548	1642	1652.3	10.124	-4.2	24.25	-8.021	189.457	136.349	-90.949	45.4
6/19/2010 7:17:...	25665	25839.2	173.9716000000...	1644	1643.5	-0.53200000000...	-7.8	38.8	-8.021	177.8180000000...	69.072	-28.672	40.4
6/19/2010 7:18:...	25679	25825.5	146.6875	1646	1641.9	-3.78600000000...	-4.8	29.1	-8.021	157.2539	21.422	14.078	35.5
6/19/2010 7:19:...	25704	25821.1	117.1025000000...	1647	1640.4	-6.73799999999...	-7.8	33.95	-8.021	127.4667000000...	11.221	19.279	30.5
6/19/2010 7:20:...	25729	25821	91.81749999999...	1649	1647.8	-0.79000000000...	-7.2	9.7	-8.021	118.9244999999...	11.835	13.865	25.7
6/19/2010 7:21:...	25754	25832.7	78.33250000000...	1650	1651.8	1.75800000000...	-11.3	43.65	-8.021	72.75630000000...	0.832999999999...	20.667	21.5
6/19/2010 7:22:...	25780	25805.8	26.24749999999...	1651	1648.2	-3.2940000000001	-6.1	9.7	-8.021	53.83409999999...	27.64	-5.04	22.6
6/19/2010 7:23:...	25790	25803.1	13.29310000000...	1652	1648.1	-3.46799999999...	-7.9	33.95	-8.021	17.89430000000...	42.838	-18.138	24.7
6/19/2010 7:24:...	25785	25804.2	19.06929999999...	1650	1641.5	-8.76400000000...	-7.9	33.95	-8.021	29.33089999999...	35.03	-8.33	26.7
6/19/2010 7:25:...	25780	25801.8	21.34549999999...	1649	1640.7	-8.25999999999...	-7.4	29.1	-8.021	36.67549999999...	15.715	13.085	28.8
6/19/2010 7:26:...	25776	25792.1	16.32170000000...	1648	1640	-7.65599999999...	-9.1	4.85	-8.021	57.837100000004	44.971	-14.071	30.9

Data Processing

A visual inspection of the provided data revealed that the data sets contain instances of bad data, such as outliers, spikes and missing points. Two approaches are used to detect and eliminate bad data. The first approach identifies the bad data by detecting sudden changes. The second approach is based on a standard outlier-detection algorithm, such as the *k*-sigma criterion (sigma is the standard deviation of the examined data set).

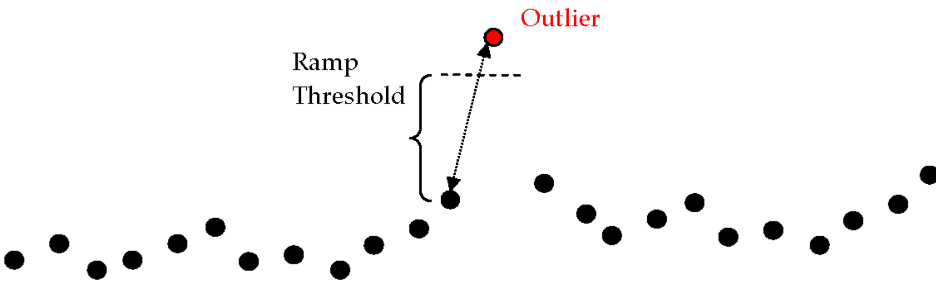
Sudden-Change Detection

Point x_t does not belong to time series X if

$$\Delta_t = |x_t - x_{t-1}| > \Delta_{\max} \quad , \qquad (33)$$

where Δmax is a threshold ramp value (Figure 30)

Figure 30. Sudden-Change Detection



Outlier Detection

Point x_t does not belong to time series X if

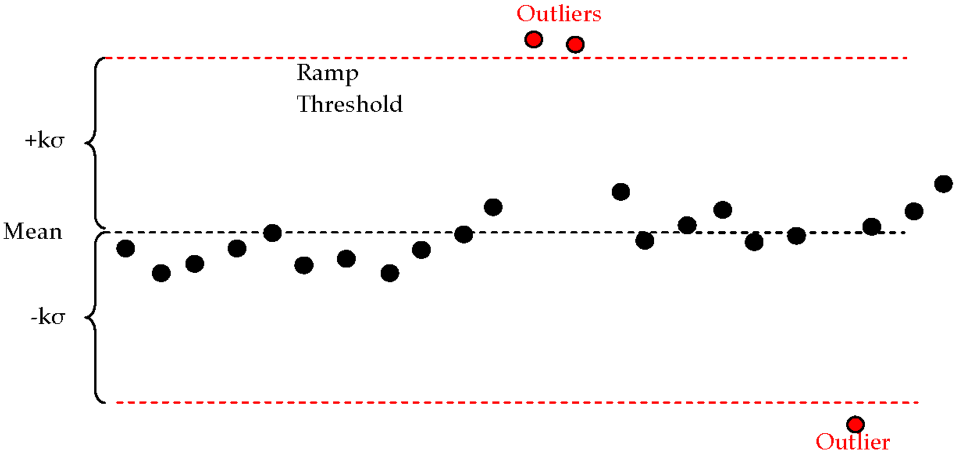
$$\begin{cases} x_t > \mu + k\sigma \\ x_t < \mu - k\sigma \end{cases}, \tag{34}$$

where σ is standard deviation;

μ is mean value;

k is the deviation factor (Figure 31).

Figure 31. Outlier Detection



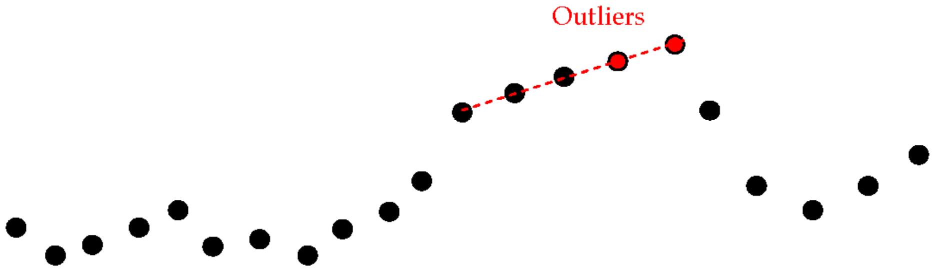
Straight-Line Detection Algorithm

To replace the missing points, the OSISoft® PI database uses an interpolation (connecting the beginning and the end of the region with missing data by a line). These points should be excluded from the statistical analysis (Figure 32).

Point x_t does not belong to time series X, if

$$x_t - x_{t-1} = x_{t-1} - x_{t-2} = x_{t-2} - x_{t-3}$$

Figure 32. Straight-Line Detection



CHAPTER 4
Simulation Results

As an example, the analysis provided below is performed for 12/12/2010. A 30-day historical window is used. Regulation requirements are calculated for a 90% level of confidence.

Method I

Statistical Analysis

The regulation requirements curve for a 30-day window is presented in Figure 33. To estimate the hourly-specific regulation requirement, the statistical analysis is performed separately for each operating hour. For each hour, a distribution of regulation requirement is calculated. Figure 34 – Figure 36 show distributions of regulation requirements for HE1, HE5 and HE17, respectively. Differences in statistical characteristics of the regulation requirements for different hours are apparent (Table 3).

Figure 33. Regulation Requirements Curve (Method I)

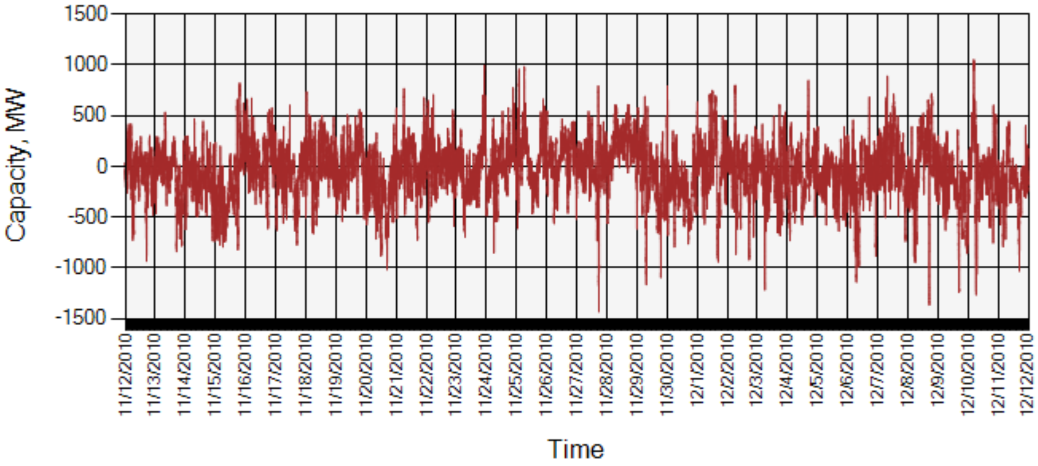


Figure 34. Distribution Histogram of Regulation Requirements (Method I) for Hour Ending 1 (HE1)

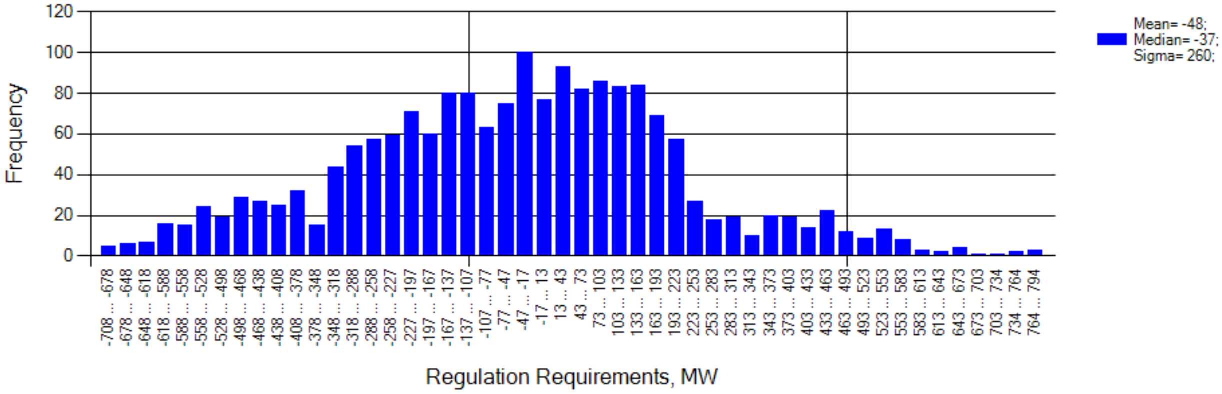


Figure 35. Distribution Histogram of Regulation Requirements (Method I) for Hour Ending 5 (HE5)

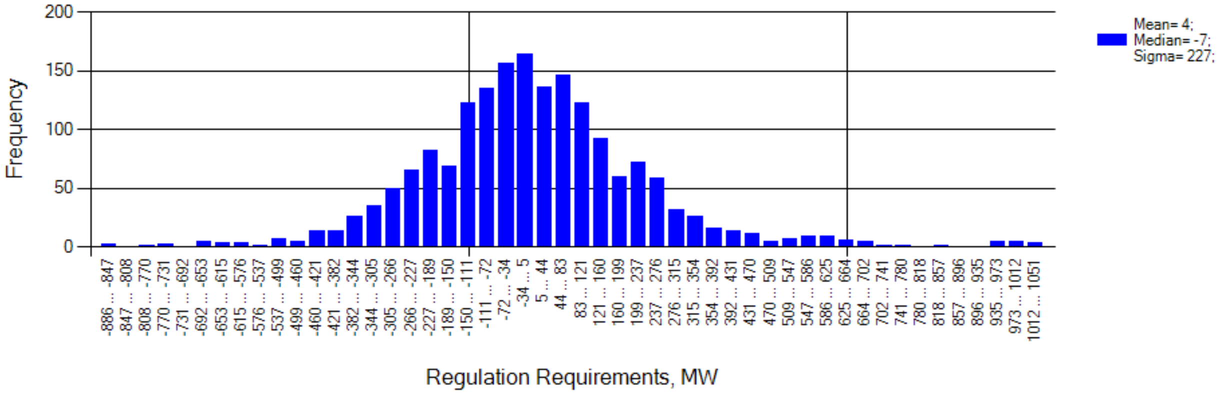


Figure 36. Distribution Histogram of Regulation Requirements (Method I) for Hour Ending 17 (HE17)

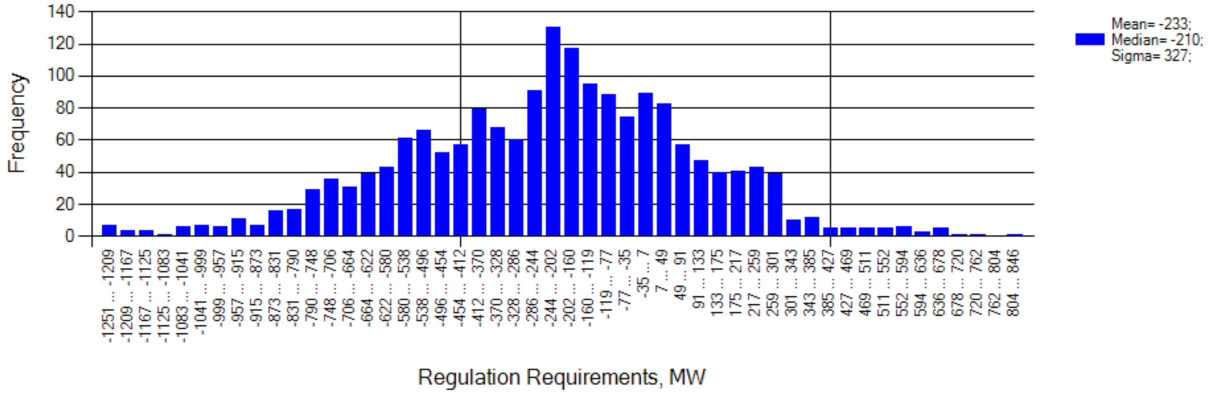


Table 3. Statistical Characteristics of Regulation Requirements (Method I)

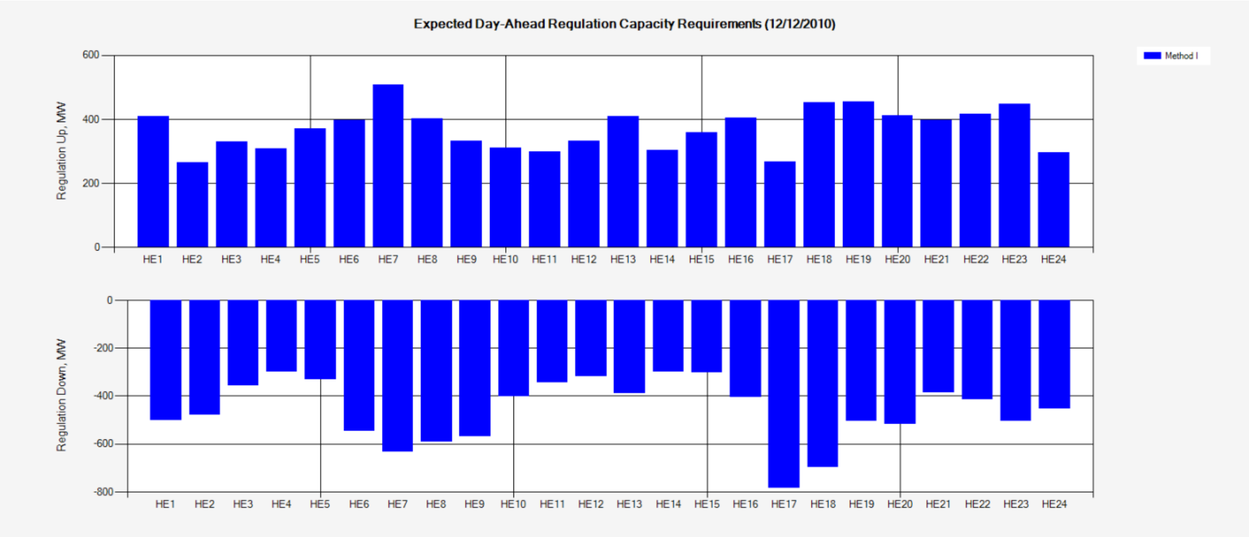
Hour	Mean	Median	Standard Deviation	Min	Max
1	-48	-37	260	-708	794
2	-47	-22	233	-731	957
3	5	19	209	-717	703
4	-13	-24	197	-791	529
5	4	-7	227	-886	1051
6	-36	-28	289	-1216	706
7	-61	-60	342	-1264	983
8	-68	-50	301	-1165	889
9	-85	-57	276	-988	587

10	-40	-38	222	-971	541
11	-22	-38	202	-616	712
12	-5	-10	214	-880	603
13	-33	-58	235	-848	748
14	-12	-21	191	-594	589
15	-21	-47	214	-529	696
16	-9	-14	236	-688	553
17	-233	-210	327	-1251	846
18	-158	-168	361	-1433	792
19	-58	-70	265	-901	801
20	12	32	275	-1094	821
21	37	60	228	-753	602
22	1	13	251	-782	774
23	-22	-14	293	-885	997
24	-55	-45	230	-858	500

Regulation-Requirements Prediction

An estimation of hourly-specific regulation requirements for a 90% confidence level is presented in Figure 37. It can be observed that regulation requirements have a pattern. The shape of the pattern is specified by the morning and evening and morning ramps, switching of the pump hydro units and other factors.

Figure 37. Regulation Requirements (Method I) for 12/12/2010



Method 2

Statistical Analysis

A regulation-requirements curve for a 30-day window calculated using (14) is presented in Figure 38. To estimate the hour-specific regulation requirement, a statistical analysis is performed separately for each hour. Figure 39 – Figure 41 show distributions of regulation requirement for HE1, HE5 and HE17, correspondingly. Hourly specific statistical characteristics of the regulation requirements calculated by Method II are given in Table 4.

Figure 38. Regulation Requirements Curve (Method II)

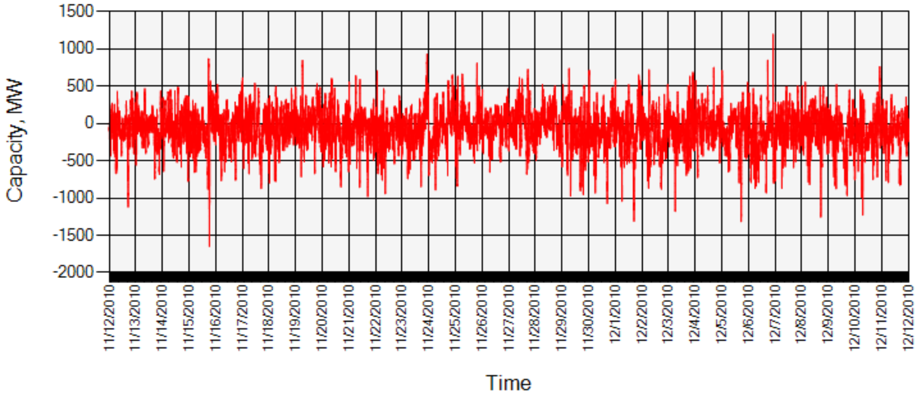


Figure 39. Distribution Histogram of Regulation Requirements (Method II) for Hour Ending 1 (HE1)

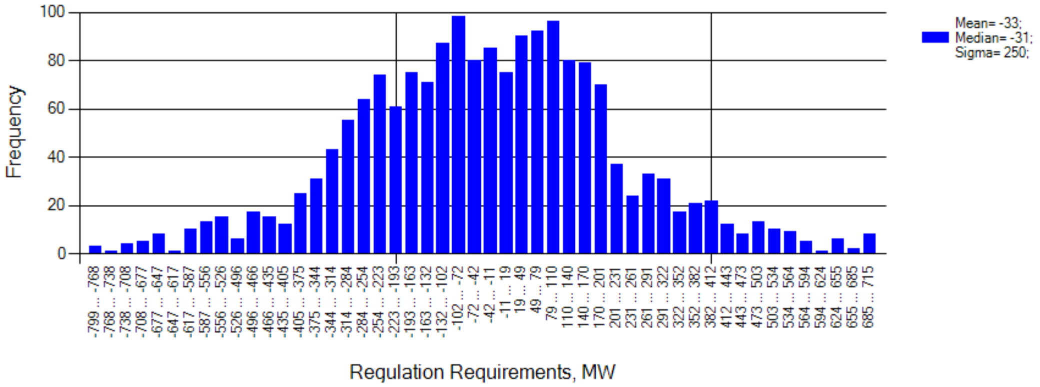


Figure 40. Distribution Histogram of Regulation Requirements (Method II) for Hour Ending 5 (HE5)

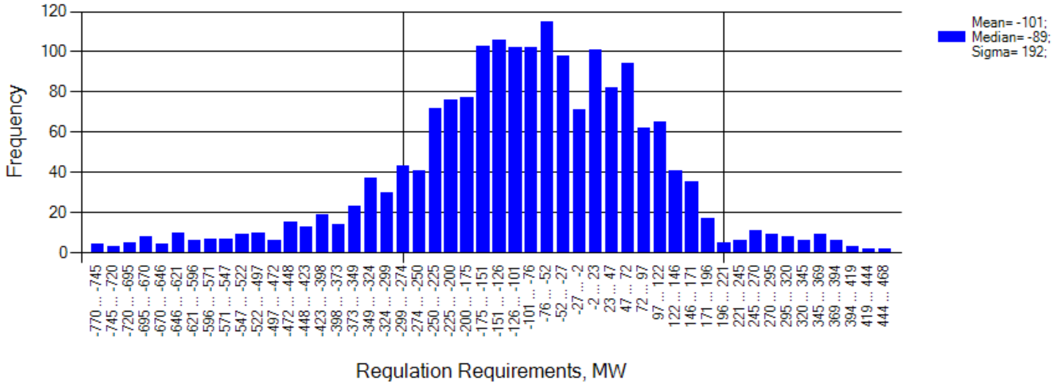


Figure 41. Distribution Histogram of Regulation Requirements (Method II) for Hour Ending 17 (HE17)

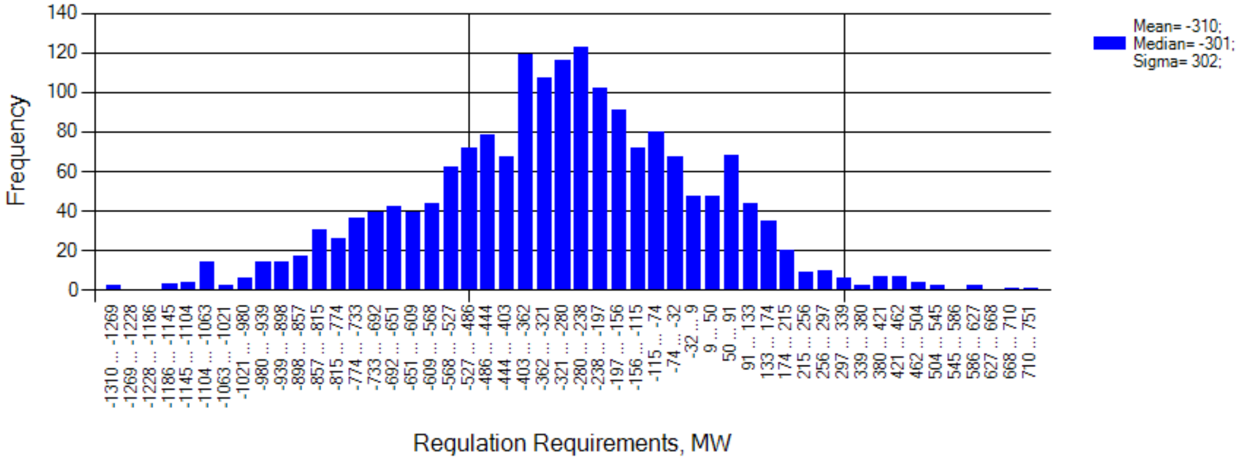


Table 4. Statistical Characteristics of Regulation Requirements (Method II)

Hour	Mean	Median	Standard Deviation	Min	Max
1	-33	-31	250	-799	715
2	-67	-65	193	-842	703
3	-48	-41	189	-793	433
4	-82	-70	169	-766	555
5	-101	-89	192	-770	468
6	-135	-104	255	-1179	430
7	-74	-63	289	-1229	847
8	-58	-49	242	-974	521
9	-76	-63	241	-942	604
10	-82	-90	192	-858	616

11	-66	-75	171	-552	496
12	-29	-31	187	-645	597
13	-80	-104	188	-543	465
14	-48	-39	161	-602	490
15	-73	-67	178	-759	473
16	-96	-82	219	-931	367
17	-310	-301	302	-1310	751
18	-119	-104	343	-1315	867
19	-95	-78	243	-1648	474
20	-14	-20	218	-953	810
21	28	29	187	-720	650
22	7	6	219	-685	685
23	-5	-27	242	-801	1196
24	-51	-62	240	-776	568

Regulation Requirement Prediction

Capacity Requirements

An estimation of hourly-specific regulation requirements for a 90% confidence level is presented in Figure 42. A comparison of regulation requirements prediction for different values of the coefficient α in equation (15) is shown in Figure 43. Varying the value of α allows us to adjust the regulation requirements range to meet the CPS2 standard. The value $\alpha = 0$ corresponds to the “ideal regulation” case (the objective is to have zero ACE all the time). One can see that using $\alpha=1$ reduces the regulation requirements range compared with lower values of α.

Figure 42. Regulation Requirements (Method II) on 12/12/2010

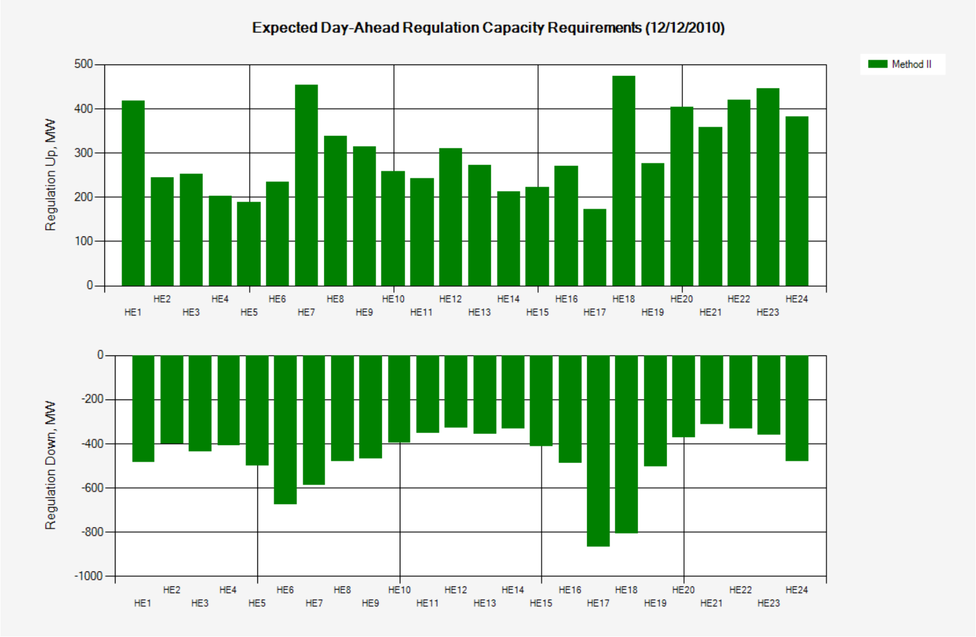
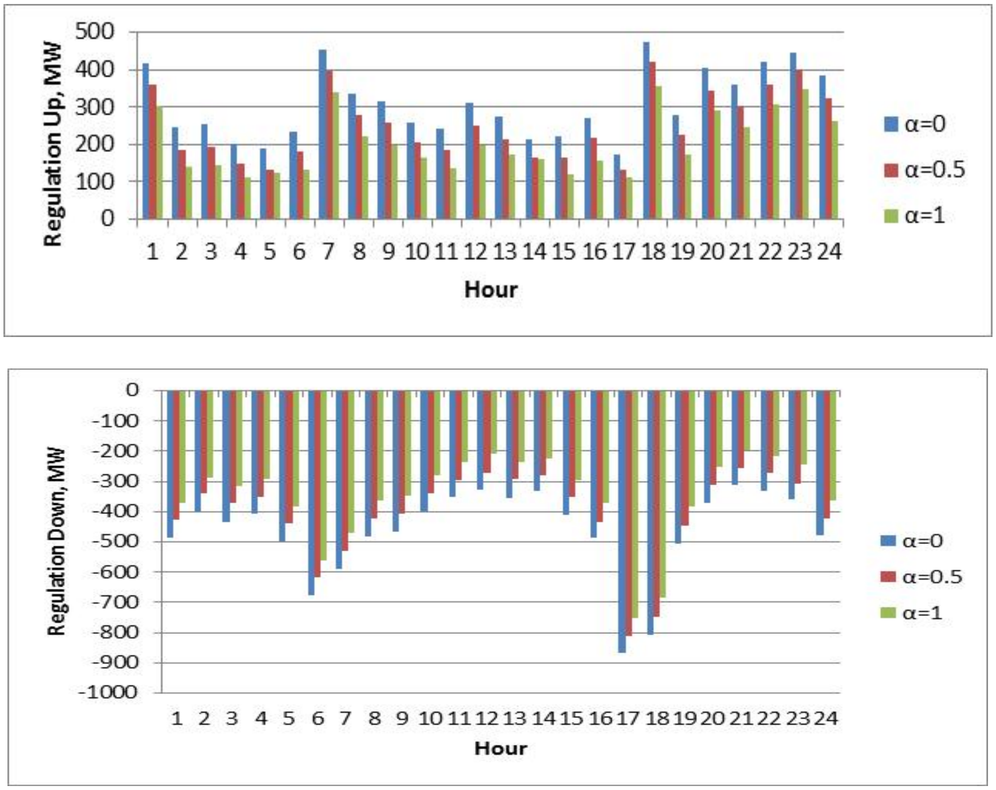


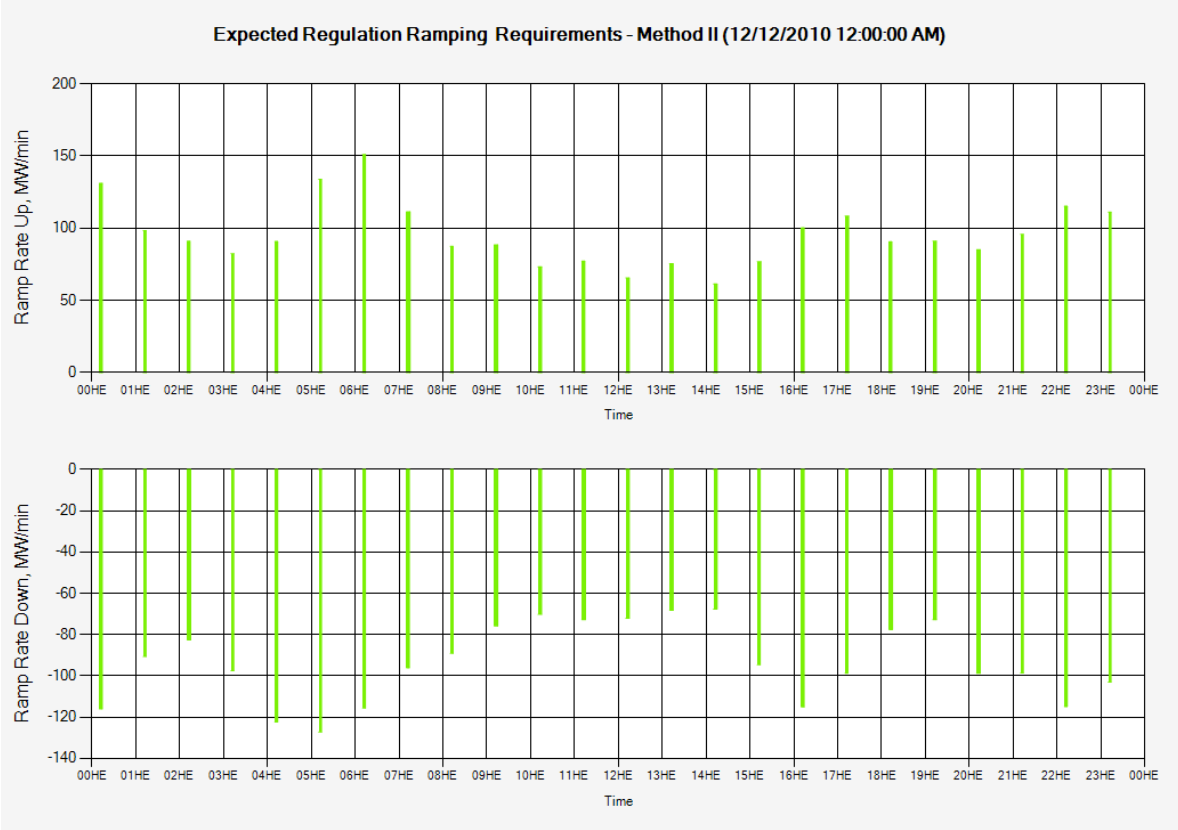
Figure 43. Comparison of Regulation Requirements (Method II): α=0, α=0.5, α=1



Ramping Requirements

Expected CAISO regulation ramping requirements in terms of ramp rate and ramp duration are shown in Figure 44 for 12/10/2010. The heights of the bars reflects the maximum ramp rates, and the widths of the bars indicate the maximum ramp duration requirements needed to meet the system needs with a certain level of confidence.

Figure 44. Regulation Ramping Requirements (Method II) on 12/12/2010



Self-Validation

A self-validation algorithm is used to validate the accuracy of the uncertainty model. A one month period was analyzed (11/1/2010 – 12/1/2010). The validation results for different confidence levels (50%, 75%, 90%, 95%, 98% and 100%) are shown in Table 5. For each confidence interval, the data points falling inside the confidence range are counted and divided by the total number of points. Good accuracy is achieved when the resulting percentage of points is close to the corresponding specified confidence level. Figure 45 shows self-validation results for November 2010. For example, for the 95% confidence level, the percentage of data points is 93.6%, which is fairly close to 95%. Thus, good accuracy is achieved. This observation is valid for all the confidence levels (Figure 45).

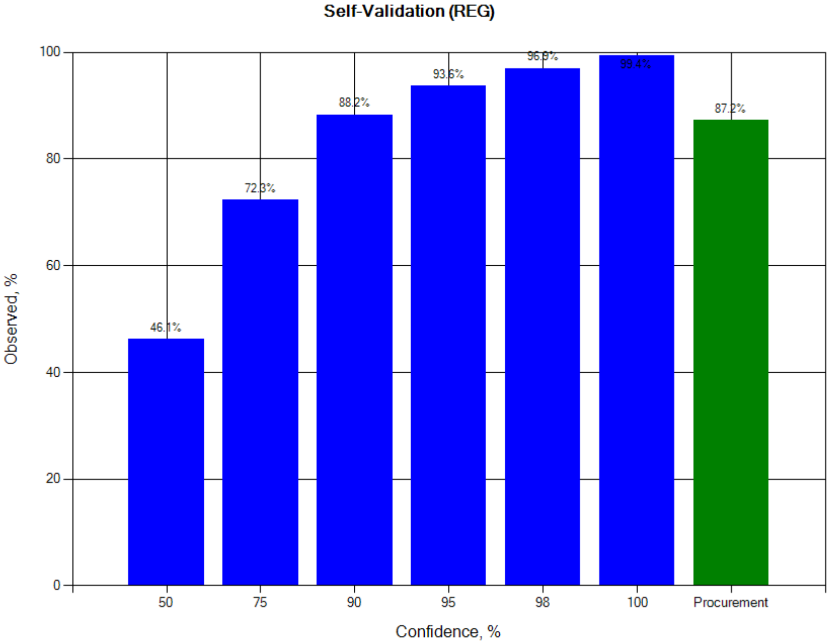
The number of points within the actual CAISO day-ahead regulation procurement range was also calculated to compare the existing performance against the performance of the proposed approach. In total, 87.2% of the points are found within the CAISO day-ahead procurement range (Figure 45).

Table 5. Self-Validation Results

Date	50%	75%	90%	95%	98%	100%	CAISO Procurement
11/1/2010 0:00	596 (41%)	935 (65%)	1186 (82%)	1331 (92%)	1420 (99%)	1437 (100%)	1256 (87%)
11/2/2010 0:00	741 (51%)	1109 (77%)	1282 (89%)	1340 (93%)	1367 (95%)	1433 (100%)	1274 (88%)
11/3/2010 0:00	667 (46%)	1024 (71%)	1208 (84%)	1278 (89%)	1349 (94%)	1422 (99%)	1205 (84%)
11/4/2010 0:00	692 (48%)	1114 (77%)	1266 (88%)	1325 (92%)	1381 (96%)	1429 (99%)	1320 (92%)
11/5/2010 0:00	666 (46%)	1094 (76%)	1297 (90%)	1358 (94%)	1408 (98%)	1429 (99%)	1282 (89%)
11/6/2010 0:00	800 (56%)	1177 (82%)	1361 (95%)	1422 (99%)	1435 (100%)	1440 (100%)	1282 (89%)
11/7/2010 0:00	559 (39%)	869 (60%)	1104 (77%)	1222 (85%)	1303 (90%)	1421 (99%)	1131 (79%)
11/8/2010 0:00	604 (42%)	914 (63%)	1190 (83%)	1306 (91%)	1370 (95%)	1421 (99%)	1227 (85%)
11/9/2010 0:00	656 (46%)	1073 (75%)	1302 (90%)	1386 (96%)	1418 (98%)	1440 (100%)	1262 (88%)
11/10/2010 0:00	736 (51%)	1107 (77%)	1334 (93%)	1383 (96%)	1417 (98%)	1436 (100%)	1318 (92%)
11/11/2010 0:00	517 (36%)	974 (68%)	1278 (89%)	1334 (93%)	1387 (96%)	1440 (100%)	1337 (93%)
11/12/2010 0:00	806 (56%)	1168 (81%)	1297 (90%)	1361 (95%)	1406 (98%)	1433 (100%)	1318 (92%)
11/13/2010 0:00	839 (58%)	1164 (81%)	1383 (96%)	1418 (98%)	1432 (99%)	1440 (100%)	1355 (94%)
11/14/2010 0:00	691 (48%)	1095 (76%)	1305 (91%)	1371 (95%)	1406 (98%)	1440 (100%)	1307 (91%)
11/15/2010 0:00	578 (40%)	1004 (70%)	1238 (86%)	1317 (91%)	1356 (94%)	1402 (97%)	1184 (82%)
11/16/2010 0:00	568 (39%)	962 (67%)	1275 (89%)	1368 (95%)	1406 (98%)	1432 (99%)	1238 (86%)
11/17/2010 0:00	594 (41%)	977 (68%)	1255 (87%)	1349 (94%)	1407 (98%)	1440 (100%)	1193 (83%)
11/18/2010 0:00	713 (50%)	1092 (76%)	1311 (91%)	1361 (95%)	1415 (98%)	1440 (100%)	1358 (94%)
11/19/2010 0:00	693 (48%)	1039 (72%)	1291 (90%)	1365 (95%)	1410 (98%)	1431 (99%)	1298 (90%)

11/20/2010 0:00	607 (42%)	975 (68%)	1212 (84%)	1316 (91%)	1379 (96%)	1430 (99%)	1140 (79%)
11/21/2010 0:00	766 (53%)	1125 (78%)	1357 (94%)	1393 (97%)	1414 (98%)	1432 (99%)	1273 (88%)
11/22/2010 0:00	708 (49%)	1067 (74%)	1281 (89%)	1351 (94%)	1397 (97%)	1428 (99%)	1248 (87%)
11/23/2010 0:00	689 (48%)	1050 (73%)	1300 (90%)	1355 (94%)	1397 (97%)	1421 (99%)	1325 (92%)
11/24/2010 0:00	574 (40%)	942 (65%)	1206 (84%)	1312 (91%)	1392 (97%)	1438 (100%)	1199 (83%)
11/25/2010 0:00	706 (49%)	1123 (78%)	1299 (90%)	1354 (94%)	1399 (97%)	1427 (99%)	1270 (88%)
11/26/2010 0:00	818 (57%)	1243 (86%)	1408 (98%)	1432 (99%)	1434 (100%)	1440 (100%)	1348 (94%)
11/27/2010 0:00	656 (46%)	1026 (71%)	1256 (87%)	1346 (93%)	1399 (97%)	1437 (100%)	1234 (86%)
11/28/2010 0:00	604 (42%)	998 (69%)	1279 (89%)	1402 (97%)	1423 (99%)	1439 (100%)	1296 (90%)
11/29/2010 0:00	512 (36%)	856 (59%)	1174 (82%)	1300 (90%)	1377 (96%)	1418 (98%)	1118 (78%)
11/30/2010 0:00	705 (49%)	1089 (76%)	1297 (90%)	1359 (94%)	1398 (97%)	1435 (100%)	1277 (89%)
12/1/2010 0:00	611 (42%)	970 (67%)	1221 (85%)	1308 (91%)	1368 (95%)	1423 (99%)	1213 (84%)

Figure 45. Self-Validation Results (November 2010)



Financial Evaluation

Figure 46 shows the actual regulation requirements curve (dark red) observed on 12/10/2010. This curve corresponds to the “ideal” regulation – regulation needed to have zero ACE. The CAISO’s actual day-ahead regulation procurement is shown by the yellow range, and the regulation requirement predicted using Method II (at the 90% level of confidence) is shown by the gray range (Figure 46).

The CAISO day-ahead regulation procurement covers only 83% of the “ideal” regulation requirement needs (Figure 46). At the same time, 92% of the regulation requirements points (dark red curve) are found within the regulation requirements prediction range predicted by Method II (gray range).

The CAISO day-ahead regulation procurement prices for 12/10/2010 are given in Table 6. Based on this information, financial savings (or losses) due to the use of Method II are calculated. Figure 47 shows results of this financial evaluation. It can be seen that for some hours Method II proposes procuring more regulation, which would cause a financial loss (negative savings), and for some hours Method II suggests procuring less regulation, resulting in a financial savings. In total, using regulation prediction requirements calculated by Method II allows CAISO to save about $15,000 (13%) (Table 7).

Figure 46. Method II vs. CAISO Day-Ahead Regulation Procurement

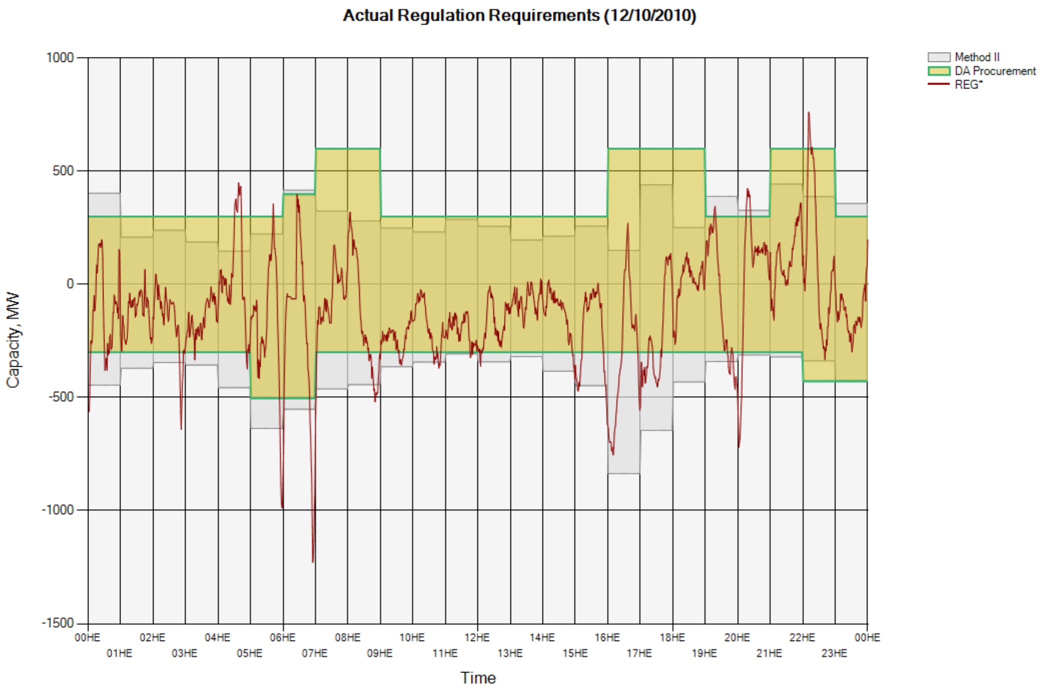


Table 6. CAISO Day-Ahead Regulation Price ($/MW) on 12/10/2010

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

Figure 47. Savings from use of Method II – Total Savings $14,600 (13%)

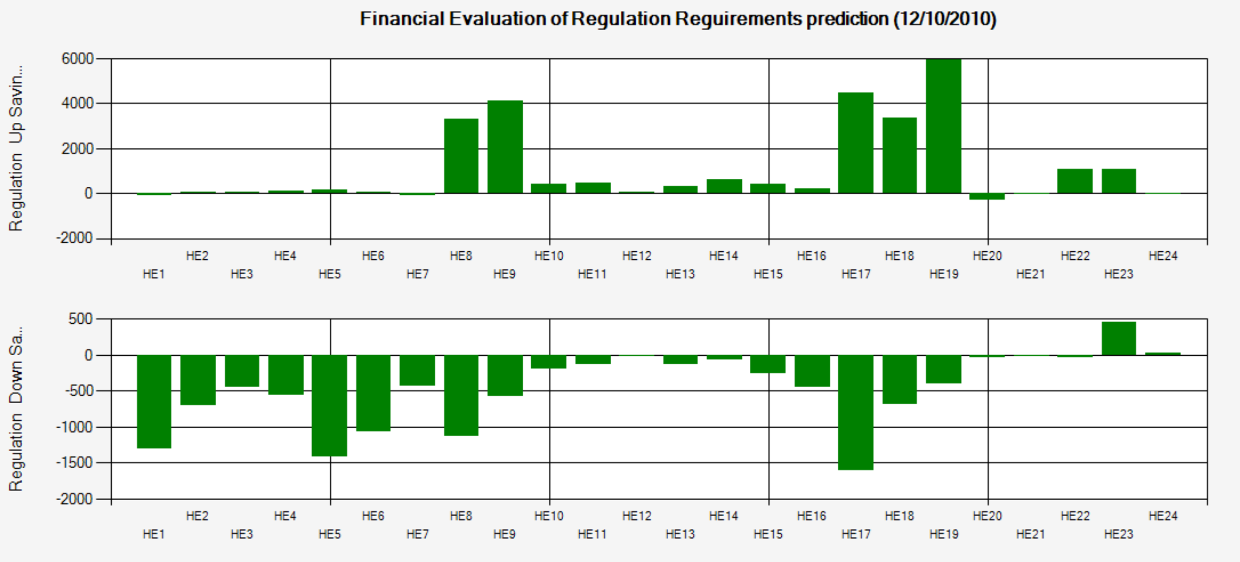


Table 7. Cost Comparison of Actual Regulation Procurement and Method II Prediction for (12/10/2010)

	Percentage of points within the range	**Regulation Procurement Total Cost**
CAISO Day-Ahead Regulation Procurement	83%	$112,200
90%-Confidence Regulation Requirements (Method II)	92%	$97,500
Savings		$14,600 (13%)

Method III

Statistical Analysis

CAISO statistical information on the actual ACE, frequency, and regulation applied to the system was used. Figure 48 and Figure 49 show CAISO ACE* (red curve) and the BAAL limit (tan). Recall that "ACE*" is the value that ACE would be if regulation were not applied. There are several instances when regulation control actions may be needed (blue circles) to meet the BAAL requirements.

Figure 48. CAISO ACE* vs. BAAL Limit on 12/10/2010

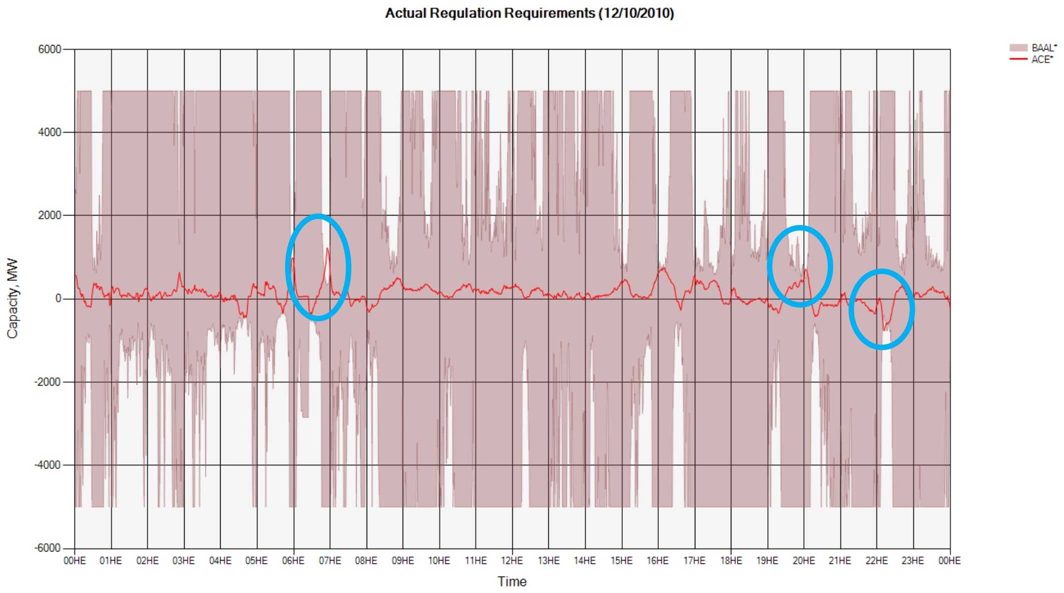
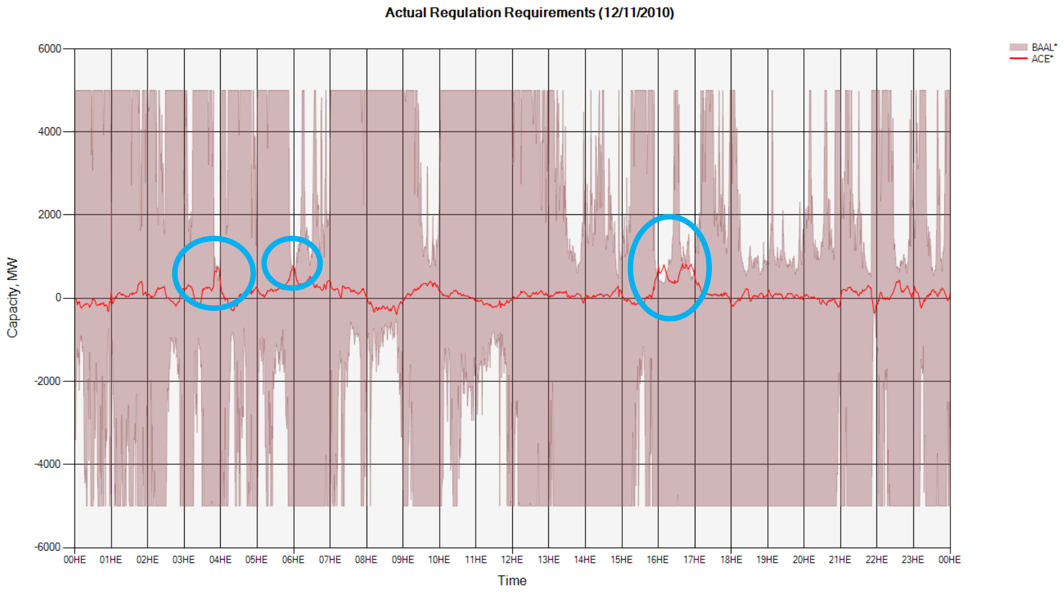


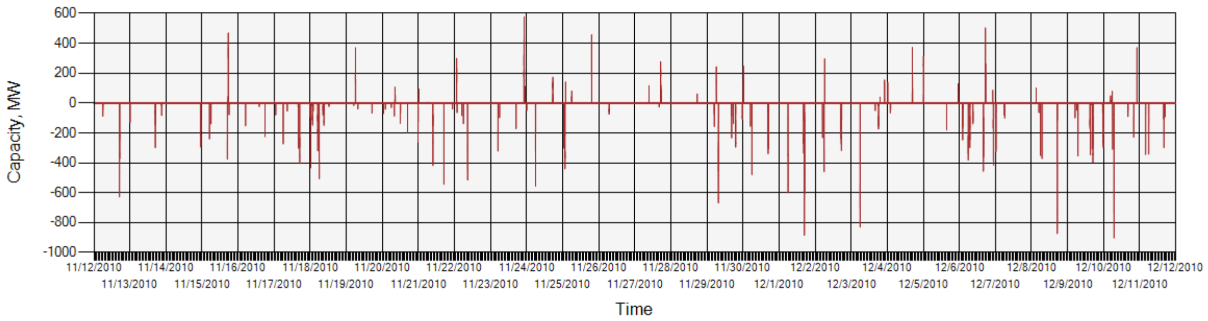
Figure 49. CAISO ACE* vs. BAAL Limit on 12/11/2010



Based on empirical data for November 12 through December 12, 2010, the CAISO required-regulation curve needed to meet the BAAL standard requirements were analyzed and the results are shown in Figure 50. Figure 50 also shows that if BAAL considerations are taken alone, no hourly regulation would be needed for several hours, though sometimes regulation (up to 500 – 800 MW) would still be required.

There are other considerations that may require regulation on a continuous basis, even if the BAAL-based criteria do not reveal this requirement. For example, a BA with a large negative ACE could accumulate inadvertent energy.

Figure 50. Regulation Requirements Curve (Method III)



Prediction of Regulation Requirements

Based on the statistical analysis of the curve presented in Figure 50, the hourly specific regulation requirements were calculated (Figure 51).

Figure 51. Regulation Requirements predicted by Method III for 12/12/2010

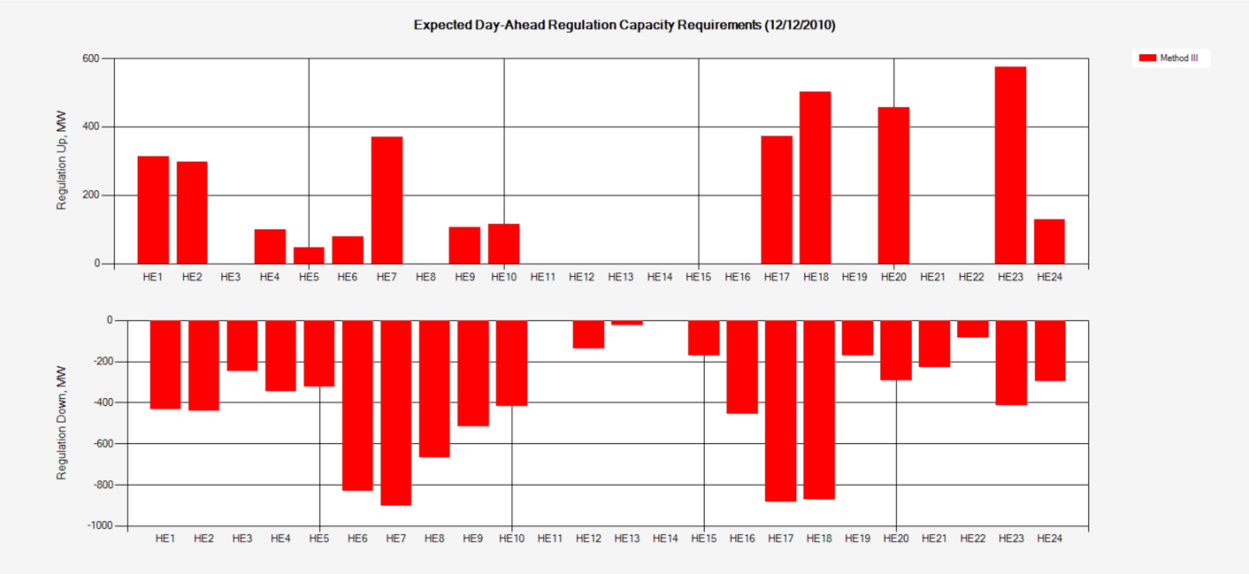
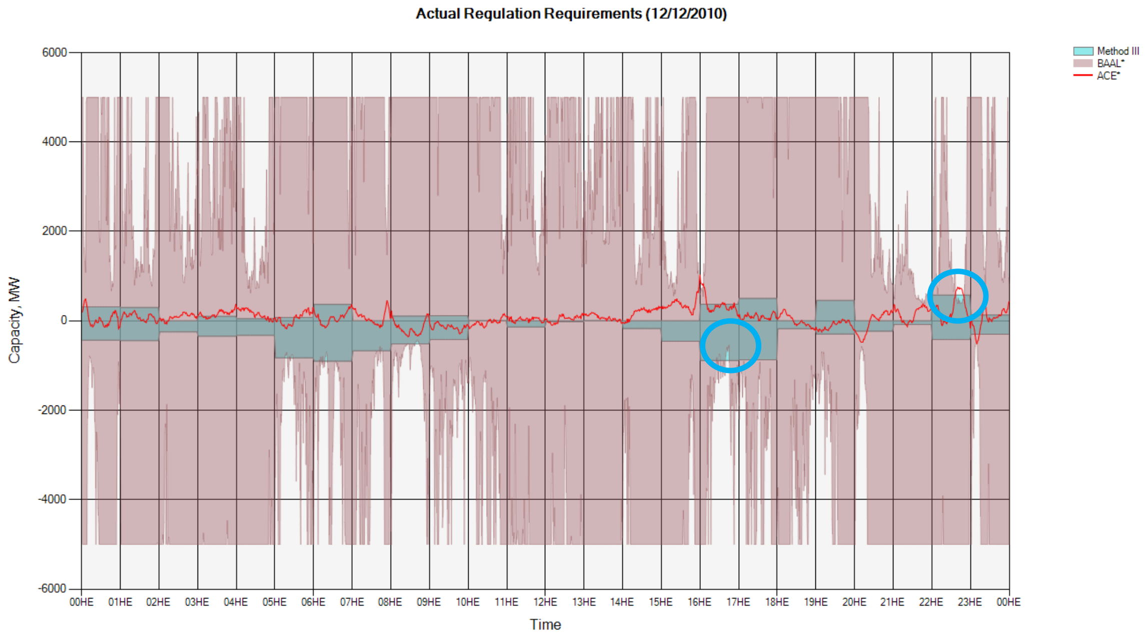


Figure 52 shows the ACE, BAAL limit and predicted regulation requirements for 12/12/2010. It can be seen from Figure 52 that the predicted amount of regulation predicted by Method III is sufficient to keep ACE* within the BAAL limit.

Figure 52. CAISO's ACE*, BAAL Limit and Regulation Predicted by Method III for 12/12/2010

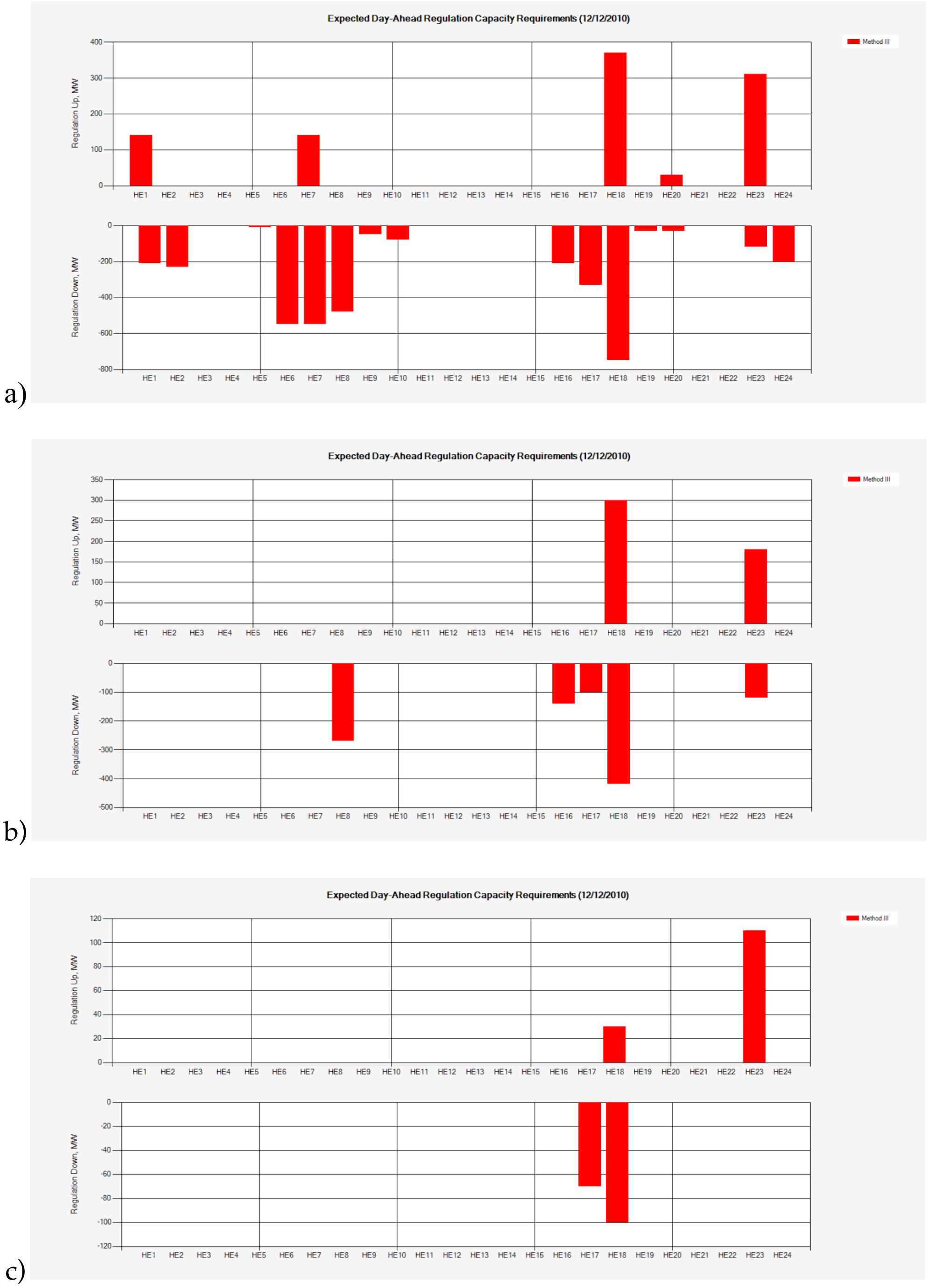


Timing Component

Regulation prediction results provided above (in Figure 51) were calculated for a maximum allowed time of BAAL limit violation $T_{max} = 0$ (see the Timing Component section of this report for details). Regulation requirement estimates for $T_{max} = 5$, 10 and 15 min are shown in Figure 53.

Introducing the timing component reduces the regulation requirements. The BAAL standard allows having ACE outside the BAAL limits for up to 30 minutes. Therefore a reasonable value of T_{max} can be around 15 minutes. Thus the amount of procured regulation can essentially be decreased without compromising system performance. Simulations have shown that for some operating hours there is no need for regulation to meet the BAAL standard.

**Figure 53. Method III Estimates of CAISO Regulation Requirements Estimation to Meet BAAL Requirements:
a) T_{max}=5 min; b) T_{max}=10 min; c) T_{max}=15 min**



Safety Margin

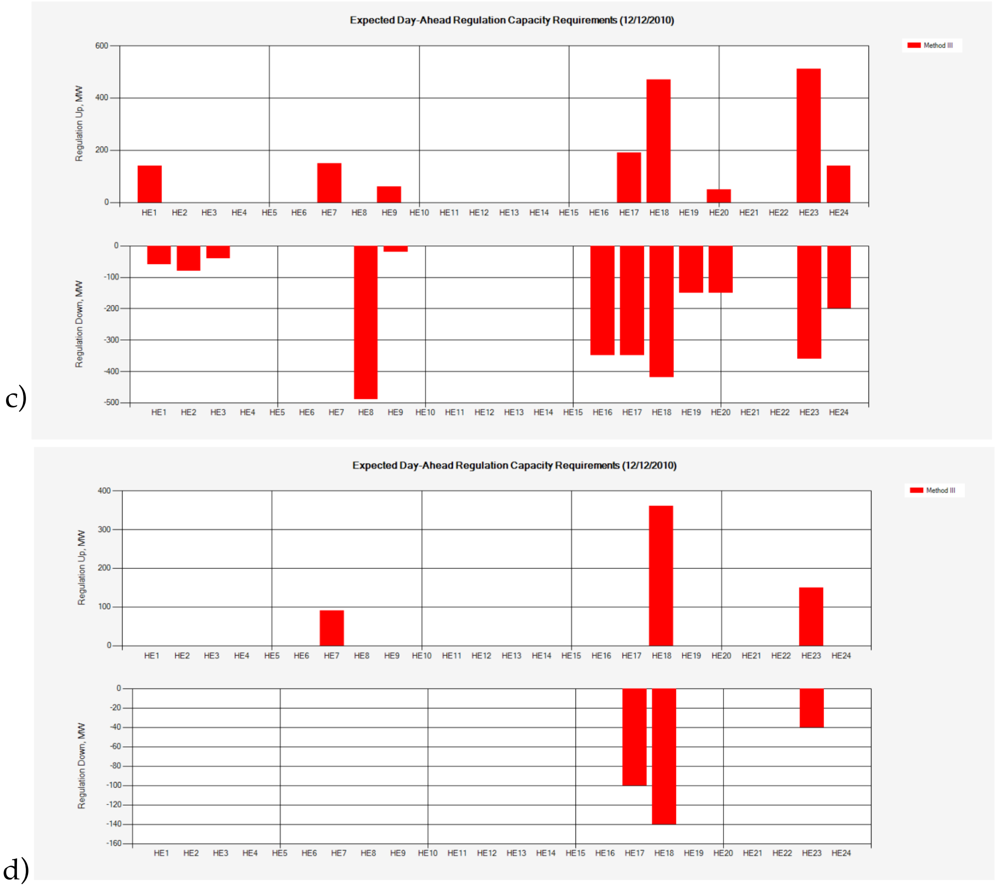
The effect of the safety margin on regulation requirements was studied. Safety margins of 1,000 MW for generation tripping and 250 MW for load drop were used (see the Safety Margin section earlier in this report for details). The regulation requirements estimates for T_{max} = 0, 5, 10 and 15 min are shown in Figure 54.

Introducing the safety margin increases the regulation requirements, but allows us to make sure that in case of contingencies the BAAL standard will not be violated. If the timing component is not applied the regulation requirements are fairly high; however, if the timing component is used (T_{max} is more than 10 minutes), the impact of the safety margin on regulation requirements is minor.

Figure 54. CAISO Regulation Requirements Estimated by Method III to Meet the BAAL Standard with Various Safety Margins: a) T_{max} = 0 minutes; b) T_{max} = 5 minutes; c) T_{max} = 10 minutes; d) T_{max} = 15 minutes

a)

b)

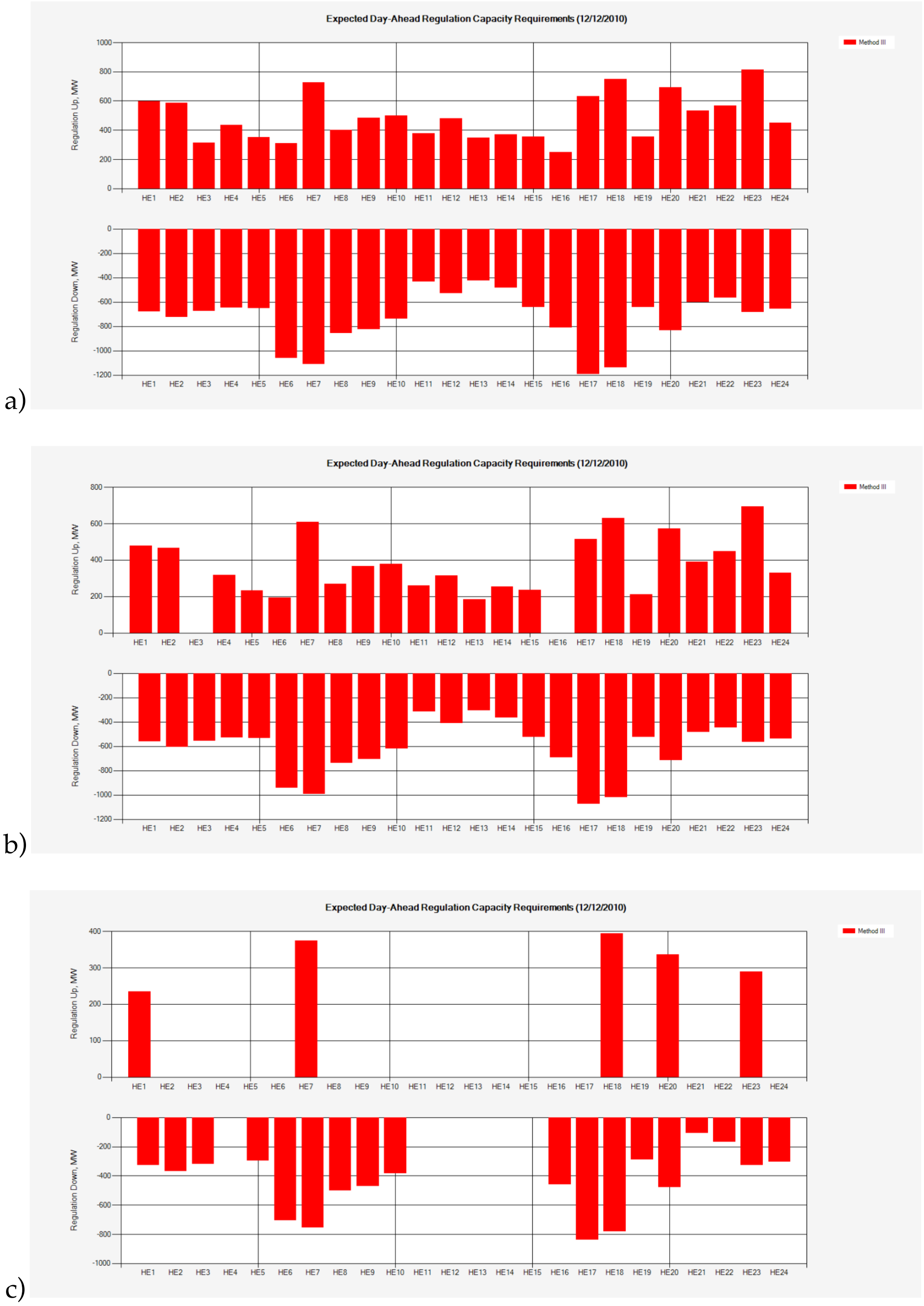


Additional N×L_{10} Constraint

The impact of additional N×L_{10} constraints on the regulation requirements was also studied. Figure 55 shows regulation requirements predictions to meet the BAAL standard and keep the ACE within 1×L_{10}, 2×L_{10}, and 4×L_{10} limits.

Simulations have shown that introducing additional N×L_{10} constraints increases the regulation requirements, especially for N=1; this can be explained by the fact that in this case the BA's ACE would be always within ±L_{10} limits.

Figure 55. CAISO Regulation Requirements Estimated with Method III to Meet the BAAL Standard with Additional Constraints: a) 1×L_{10}; b) 2×L_{10}; c) 4×L_{10}

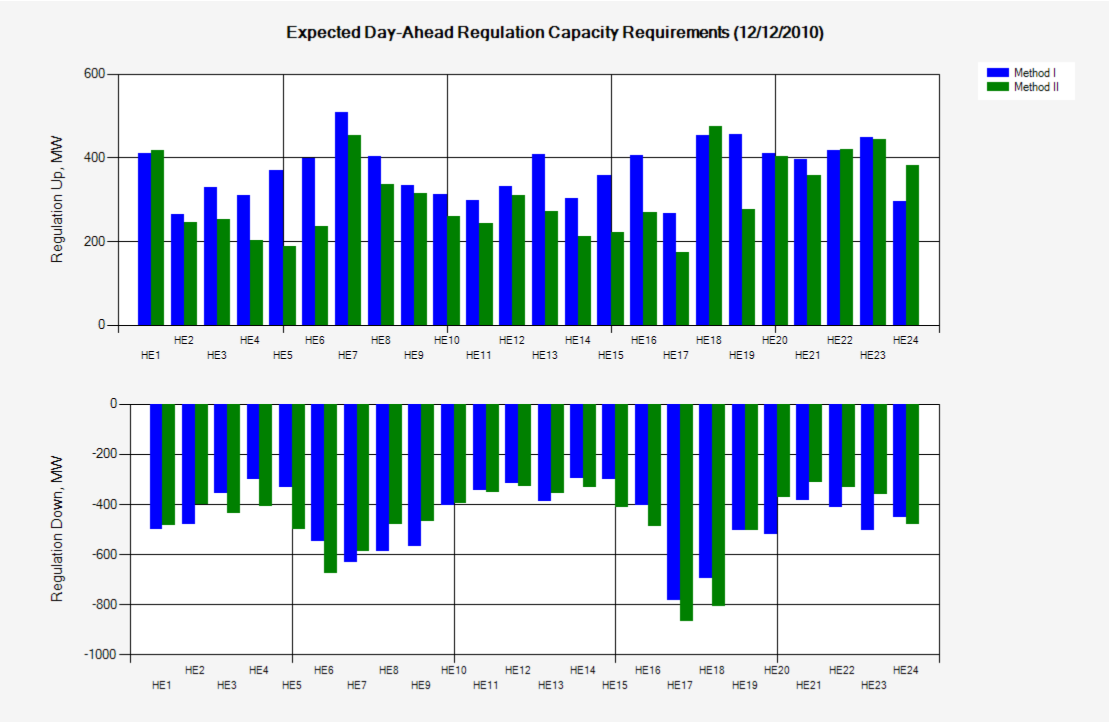


Comparison of Results from Methods I, II and III

Regulation Requirements

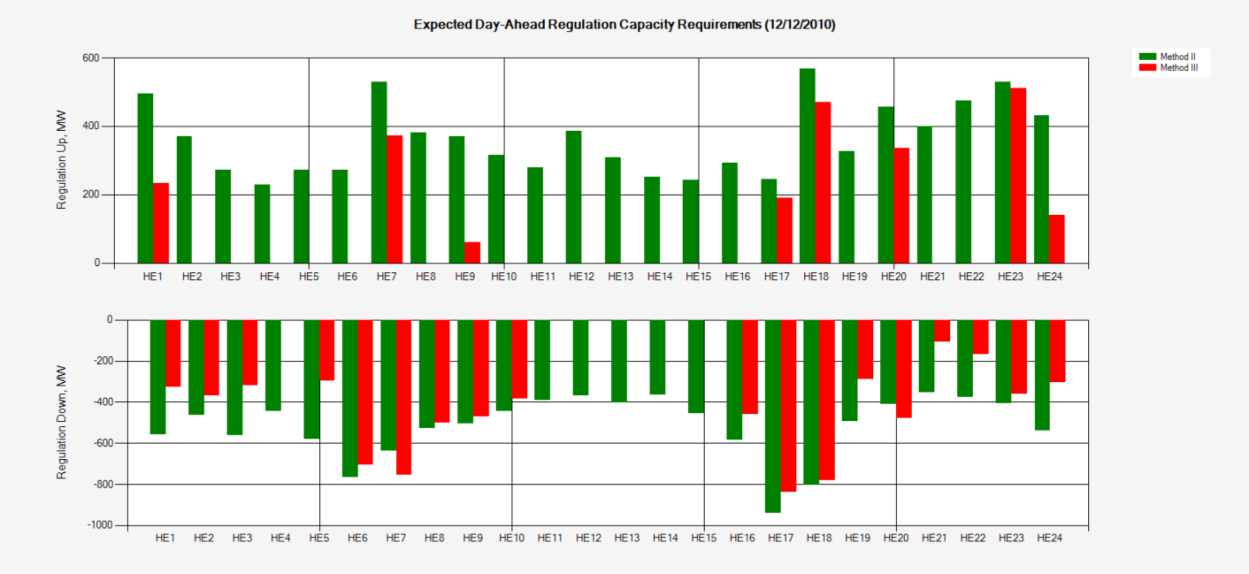
Figure 56 shows a comparison of the regulation requirements calculated using Methods I and II. Ideally, results of applying these two methods should be close, but nevertheless some difference in the results can be seen; these differences can be explained by the fact that actual CAISO statistical information from multiple data sources has been used in this study. This information contains missing points, outliers, spikes, measurement errors, etc. To filter the "bad" data several approaches have been applied (see the Data Processing section of this report); this data pre-processing allows us to get relatively close results, as shown in Figure 56.

Figure 56. Method I vs. Method II



A comparison of results from Methods II and III is presented in Figure 57. The following parameters are used in Method III: $T_{max} = 10$ minutes; Safety Margin = −1000/250 MW; and $4 \times L_{10}$ control is enabled. It can be seen from the figure that CAISO regulation requirements can be essentially reduced because the BAAL standard allows a BA to operate in wider range compared with the previously enforced CPS2 standard.

Figure 57. Method II vs. Method III



Financial Evaluation

An estimation of financial benefits has been also performed in this study. Figure 58 shows the CAISO total day-ahead regulation procurement cost for the period of one month. In total, CAISO spent more than $2,000,000 for the period, an average of about $78,000 a day.

A self-validation algorithm is applied to validate the accuracy of the uncertainty prediction model and compare the performance of the existing CAISO day-ahead regulation procurement approach against the proposed model. The validation results for different confidence levels and actual CAISO day-ahead regulation procurement are shown in Figure 59. For each confidence interval, the data points falling inside the confidence range are counted. Good accuracy is achieved when the resulting percentage of points is close to the corresponding specified confidence level. A validation procedure performed for CAISO day-ahead regulation procurement shows that the actually procured regulation capacity meets the regulation requirements only 85% of the time (Figure 59).

The regulation procurement cost for Methods I, II and III has been calculated using CAISO day-ahead regulation price information. Savings on a daily basis in regulation procurement cost for Method I, II, and III are shown in Figure 60.

In total, the potential savings using Method I is about $50,000 (2%) in one month (Figure 61); Method II saves about $270,000 (11%), and Method III can save more than $900,000 (37%) in a month[1]. However, it is important to stress that the potential saving achieved by Method III can be reduced by other potential implications such as accumulation of inadvertent energy and associated costs, thus Method III assessment needs further evaluation.

Method II (at the 90% confidence level) allows keeping the regulation requirement within the predicted range in 88% of cases (versus 85% in the case of using CAISO day-ahead procurement). At the same time

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[1] Ideally, results of Method I and Method II should be close; these differences can be explained by the fact that actual CAISO statistical information from multiple data sources has been used in this study. This information contains missing points, outliers, spikes, measurement errors, etc.

it allows CAISO to save more than 10% on regulation capacity procurement. In this experiment, α = 0 was used (corresponds to the "ideal regulation" case - the objective is to have zero ACE all the time). Even more savings can be achieved if α = 1 is used.

Figure 58. CAISO Total Day-Ahead Regulation Procurement Cost

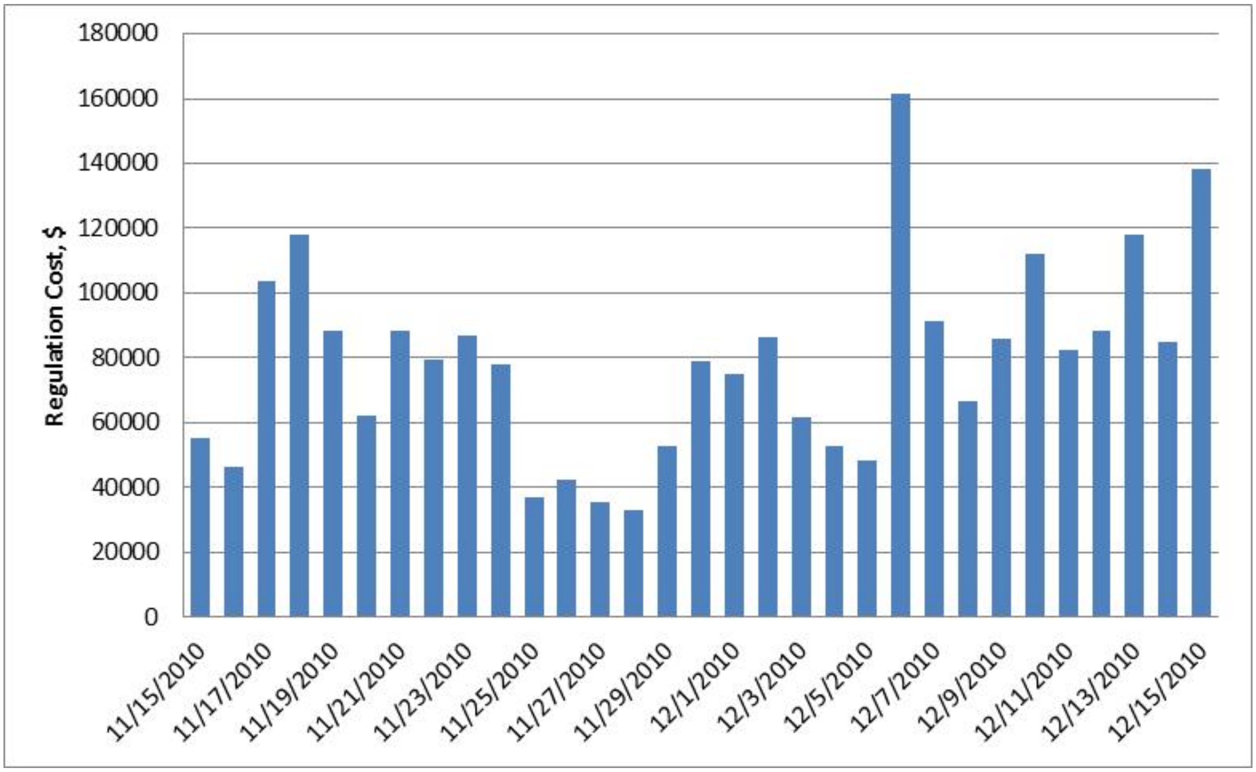


Figure 59. Self-Validation Results for the Studied Period of Time

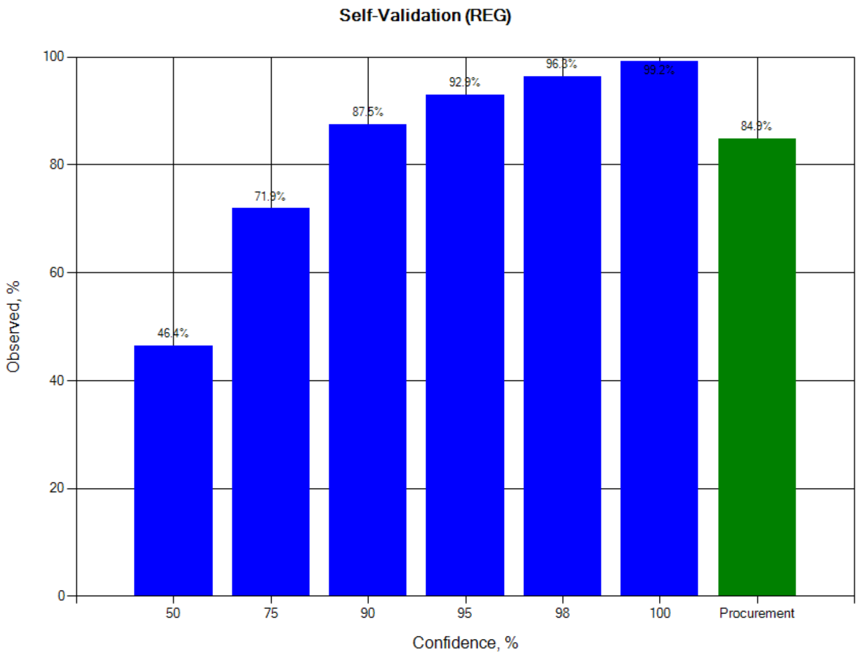


Figure 60. Regulation Procurement Daily Savings for the Three Methods

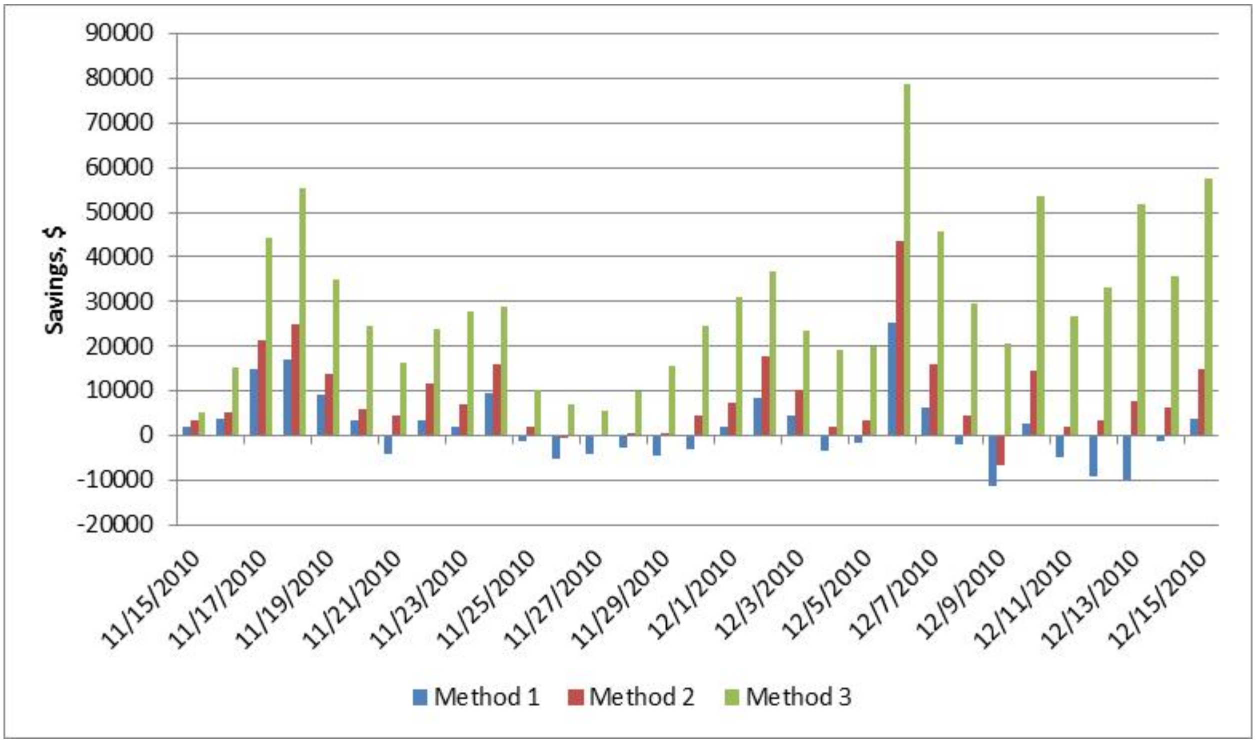
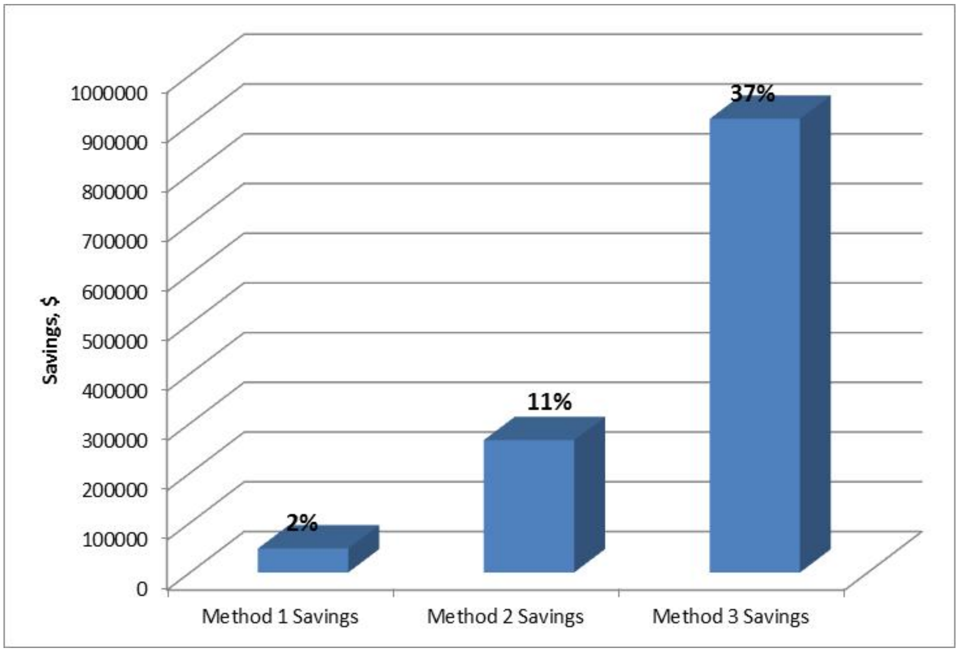


Figure 61. Regulation Procurement Monthly Savings for the Three Methods[2]



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[2] The actual saving with Method III can be lees due to the other influencing factor such as impacts on interties and inadvertent accumulation.

CHAPTER 5: Conclusions

A methodology capable of evaluating the impact of wind and solar generation, uninstructed unit deviations, and load uncertainties on the regulation requirements has been developed. As a result, the uncertainty ranges for the required regulation performance envelope can be evaluated in a day-ahead period. The generation performance envelope includes the required balancing capacity, ramping capability and ramp duration capability.

Three new methods have been developed and implemented:

- Method I is based on statistical analysis of all sources of uncertainty (load, wind generation, solar generation, uninstructed unit deviations, frequency deviations, etc.)
- Method II is based on statistical analysis of ACE and actual regulation applied to the system
- Method III evaluates regulation requirements using the BAAL standard.
    - A methodology for estimating regulation requirements that takes into account the new BAAL control performance standard has been developed.
    - Simulations have shown that CAISO regulation requirements can be essentially reduced because the BAAL standard allows BAs to operate in a wider range compared with the previously enforced CPS2 standard.
- All three methods use historical information, obtained prior to the analyzed operating day (within a moving window for a user-specified period).
- A software tool has been developed that includes a GUI, input-data outlier detection and correction algorithms, an Oracle-based database, and a self-validation procedure.

The developed software tool has the following main features:

- prediction of hourly-specific regulation requirements
- detailed visualization of input data and results
- flexibility (different confidence levels, moving-window size, optional tunings, etc.)
- statistical analysis of input data (distribution, standard deviation, mean value)
- self-validation of predicted results
- outlier detection of the input data
- capability to export results to MS Excel®.

Next Steps (Technical Area):

The proposed steps in the technical area will increase the robustness and performance of the tool while handling imperfect information typically available in control centers, improving the probabilistic models to additionally reduce regulation requirements, adding additional model components reflecting new sources of uncertainty, putting more emphasis on the regulation requirements posed by the new NERC control performance standards, and deploy the tool in the California ISO control center (and potentially in the IOUs' and other control centers in California).

The following specific steps are suggested:

I. Address data interpretation and quality issues to ensure robustness of the tool.

II. Develop and implement a new generation of statistical methods to address non-stationary characteristics of forecast errors. Further improve the accuracy and robustness of the tool.

III. Probabilistic modeling of uninstructed deviation of generating units

IV. Probabilistic modeling of system frequency to obtain dynamically changed BAAL limits that is then used in calculating regulation requirements

V. Estimated regulation requirements for the next 24 hours will be updated hourly, and self-validation technique will be implanted to warn system operator if previous estimates have large deviation from updated calculated values

VI. Provide support and adjustments needed for the trial use and actual implementation of the new BAAL control performance standard at CAISO.

VII. Get CAISO feedback on the tool performance on their control center. Address the additional requests from the CAISO. Finalize the tool for actual integration into CAISO system as a fully supported product used as part of CAISO operations.

Next Steps (Commercialization):

The purposes of the planned commercialization activities include a wide dissemination and technology transfer effort with the ultimate objective to install the tool in several control centers in California. Among these activities the highest priority tasks will include a practical deployment of the regulation prediction tool in the California ISO control center, its comprehensive testing and final adjustments. The results of this effort will create a platform for a wider reach in California by serving as an example for other control areas and utilities in this state. It is expected that several more organizations will become interested in installing PNNL's tool in their control center. In parallel with the California activities, the results of this project will be widely distributed by organizing Web seminars for the industry, presenting them at the industry forums, including UWIG, WECC groups, NERC subcommittees, and conferences. It is expected that through these activities (supported by DOE), the impact of this project will be extended from the state-wide level to the nation-wide level.

CHAPTER 6:
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CHAPTER 7: GLOSSARY

ACE	area control error
AGC	automatic generation control
BA	balancing authority
BAAL	Balancing Authority ACE Limits
CAISO	California Independent System Operator Corporation
CDF	cumulative distribution function
CPS	control performance standards
HE	hour ending
ID	identification
ISO	independent system operator
NERC	North American Electric Reliability Corporation
NI	Net Interchange
PDF	probability density function
PIER	Public Interest Energy Research
RD&D	research, development, and demonstration
PNNL	Pacific Northwest National Laboratory
SQL	Structured Query Language
WECC	Western Electricity Coordinating Council

APPENDIX A:
Assessment of Ramping Requirements

The ramping capability of the regulating unit can directly influence the required regulation and load-following capacity. If the ramping capability is insufficient, more units and more capacity must be involved in regulation to follow the ramps, in which case a simultaneous evaluation is necessary to determine the true requirements.

The required ramping capability can be derived from the shape of the regulation/load-following curve. This derivation needs to be done in a scientific way. The “swinging door” algorithm proposed for this purpose is a proven technical solution implemented in the PI Historian and widely used to compress and store time-dependent datasets.

Figure A.1 demonstrates the idea of the ”swinging door” approach. A point is classified as a ”turning point” whenever the next point in the sequence cause any intermediate point to fall outside a parallelogram defined by the admissible accuracy range $\pm\varepsilon\Delta G$. For instance, for point 3, one can see that point 2 stays inside the window abcd. For point 4, both points 2 and 3 stay within the window abef. But for point 5, point 4 lies outside the window defined between points 1 and 5, and therefore point 4 is marked as a turning point.

Based on this analysis, we conclude that points 1, 2, and 3 correspond to the different magnitudes of the regulation signal, $\pi 1$, $\pi 2$ and $\pi 3$, whereas the ramping requirement, ρ, at all these points is the same, $\rho 1\text{-}3$ (see Figure A.2) The swinging-door algorithm also helps to determine the ramp duration δ.

Figure A.1. The Concept of the “Swinging Door” Algorithm

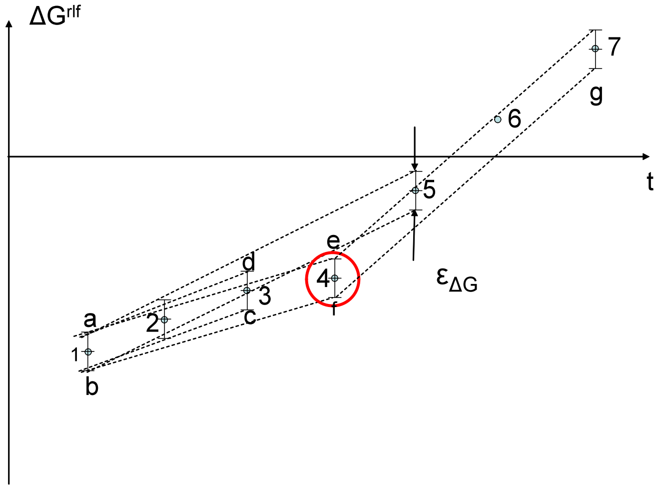
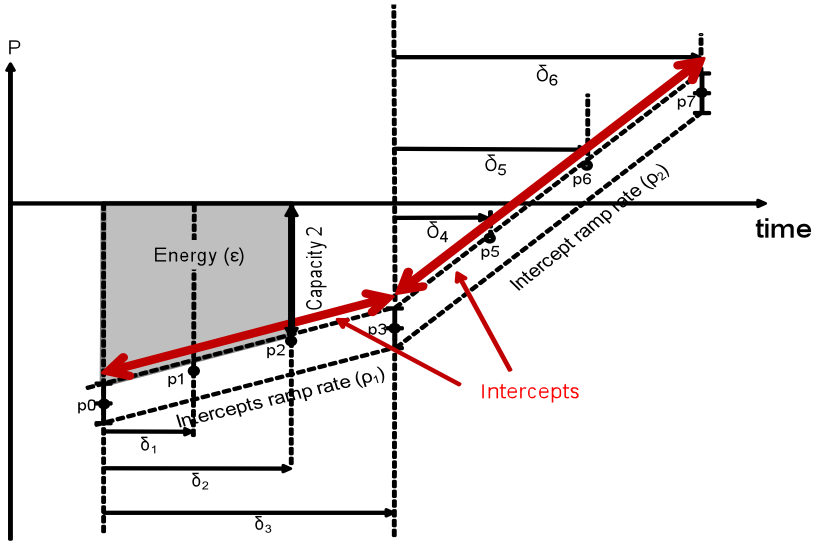
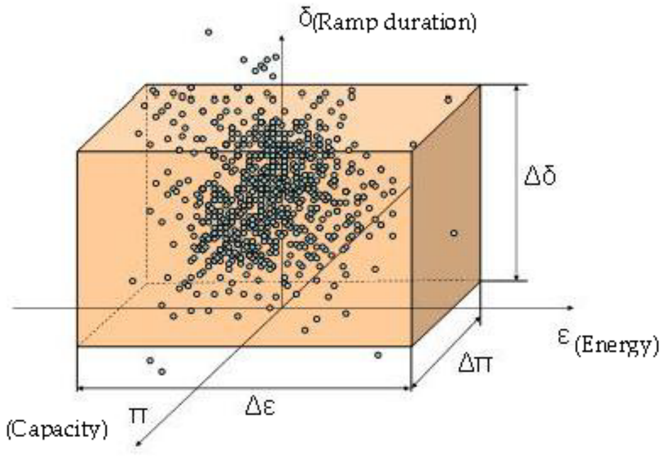


Figure A.2. "Swinging Door" Algorithm for Obtaining Regulation, Ramps, and Ramp Durations



To illustrate the idea of this approach, any three of the four dimensions can be chosen and plotted in a three-dimensional space. For example, Figure A.3 illustrates a plot of three dimensions (ε, π, δ) associated with performance envelope. Such three-dimensional plots can be applied to all other combinations as well, such as ε-π-δ, ε- π-ρ, ε- δ-ρ, and π- δ- ρ, but the actual analysis is conducted in the four-dimensional space (π = capacity, δ = ramp duration; ρ = ramp rate; ε = energy).

Figure A.3. Graphical Representation of (ε, π, δ) Dimensions in a Performance Envelope



The plot shown in Figure A.3 then facilitates the following steps.

First, choose some percentile threshold, say P%. This means that P% of all conditions will fall within the first performance envelope.

For a particular BA, and each performance envelope (including net load, load following, and regulation) to be estimated for that BA, construct a bounding box such that P% of all the points in the plot are within that box as shown in Figure A.3. Some percentage of the points, 100 - P%, will be left outside the box. This would mean that we are not going to balance against a certain percentage of extreme situations in which the components of the performance envelope exceed certain values. We then determine the dimensions of the bounding box, for instance, $\Delta\pi$, $\Delta\delta$ and $\Delta\varepsilon$, also shown in Figure A.3. These dimensions reflect the capacity, ramp, ramp duration, and energy requirements needed for each type of service (that is, for the net energy, load-following, and regulation services).

APPENDIX B:
Database Specification

Time Stamp Format Requirements

1-Minute Resolution Data

1-minute resolution data should have a 1-minute, zero-second increment. Example:

01-JAN-10 00:01.00 AM

01-JAN-10 00:02.00 AM

01-JAN-10 00:03.00 AM

etc.

5-Minute Resolution Data

5-minute resolution data should begin at a multiple of 5 and have a 5-minute, zero-second increment. Example:

01-JAN-10 00:00.00 AM

01-JAN-10 00:05.00 AM

01-JAN-10 00:10.00 AM

etc.

15-Minute Resolution Data

15-minute resolution data should begin at a multiple of 15 and have 15 minute, zero-second increment. Example:

01-JAN-10 00:00.00 AM

01-JAN-10 00:15.00 AM

01-JAN-10 00:30.00 AM

etc.

1-Hour Resolution Data

1-hour resolution data should have a 1-hour, zero-minute, zero-second increment. Example:

01-JAN-10 01:00.00 AM

01-JAN-10 02:00.00 AM

01-JAN-10 03:00.00 AM

etc.

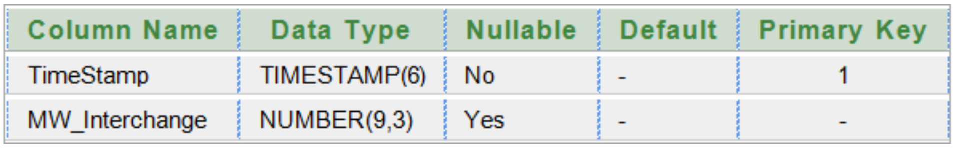
Dataset

Actual Net Interchange

Table Name = tblActualInterchangeTotal

Data Resolution = 1 min

Table B.1. Actual Net Interchange



Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
MW_Interchange	NUMBER(9,3)	Yes	-	-

TimeStamp = data point timestamp

MW_Interchange = actual net interchange (MW)

Structured Query Language (SQL) script:

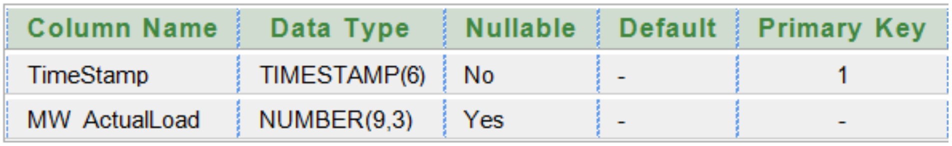
```
CREATE TABLE  "tblActualInterchangeTotal"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
        "MW_Interchange" NUMBER(9,3),
         CONSTRAINT "tblActualInterchangeTotal_PK" PRIMARY KEY ("TimeStamp")
ENABLE
   )
```

Actual Load

Table Name = tblActualLoadTotal

Data Resolution = 1 min

Table B.2. Actual Load



Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
MW ActualLoad	NUMBER(9,3)	Yes	-	-

TimeStamp = data point timestamp

MW_ActualLoad = actual total load (MW)

SQL script:

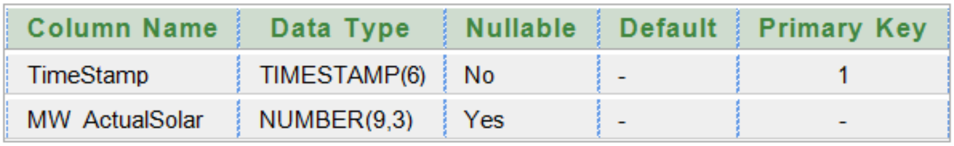
```
CREATE TABLE  "tblActualLoadTotal"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
        "MW_ActualLoad" NUMBER(9,3),
         CONSTRAINT "tblActualLoadTotal_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
```

Actual Solar Generation

Table Name = tblActualLoadTotal

Data Resolution = 1 min

Table B.3. Actual Solar Generation



Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
MW ActualSolar	NUMBER(9,3)	Yes	-	-

TimeStamp = data point timestamp

MW_ActualSolar = actual total solar generation (MW)

SQL script:

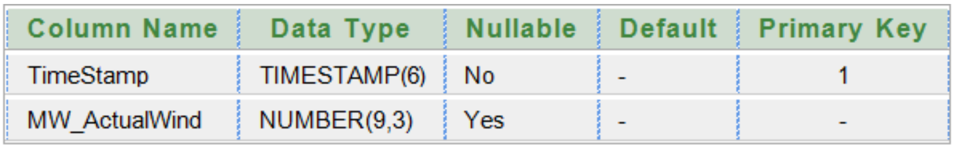
```
CREATE TABLE  "tblActualSolarTotal"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
        "MW_ActualSolar" NUMBER(9,3),
         CONSTRAINT "tblActualSolarTotal_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
```

Actual Wind Generation

Table Name = tblActualLoadTotal

Data Resolution = 1 min

Table B.4. Actual Wind Generation



Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
MW_ActualWind	NUMBER(9,3)	Yes	-	-

TimeStamp = data point timestamp

MW_ActualWind = actual total wind generation (MW)

SQL script:

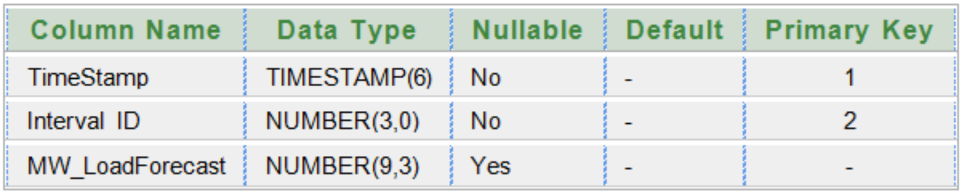
```
CREATE TABLE  "tblActualWindTotal"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
        "MW_ActualWind" NUMBER(9,3),
         CONSTRAINT "tblActualWindTotal_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
```

Real-Time Load Forecast

Table Name = tblRealTimeLoadForecastTotal

Data Resolution = 5 min

Table B.5. Real-Time Load Forecast



Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
Interval ID	NUMBER(3,0)	No	-	2
MW_LoadForecast	NUMBER(9,3)	Yes	-	-

TimeStamp = timestamp – beginning of the first interval (!)

Interval_ID = interval ID - 5 min resolution, up to 13 intervals

MW_LoadForecast = real-time total load forecast (MW)

Figure B.1. Time and Resolution

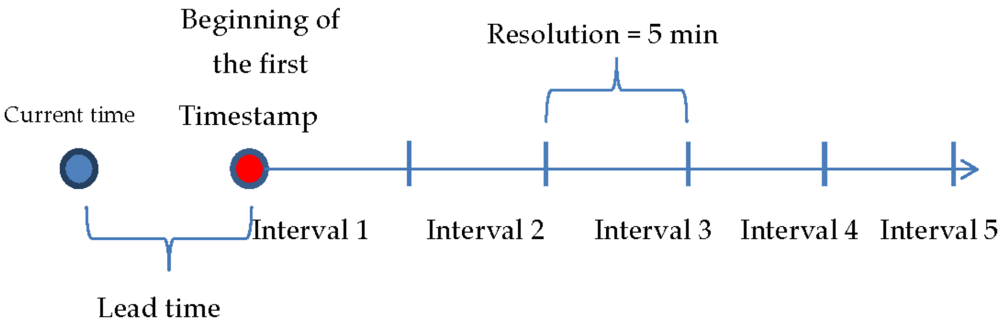
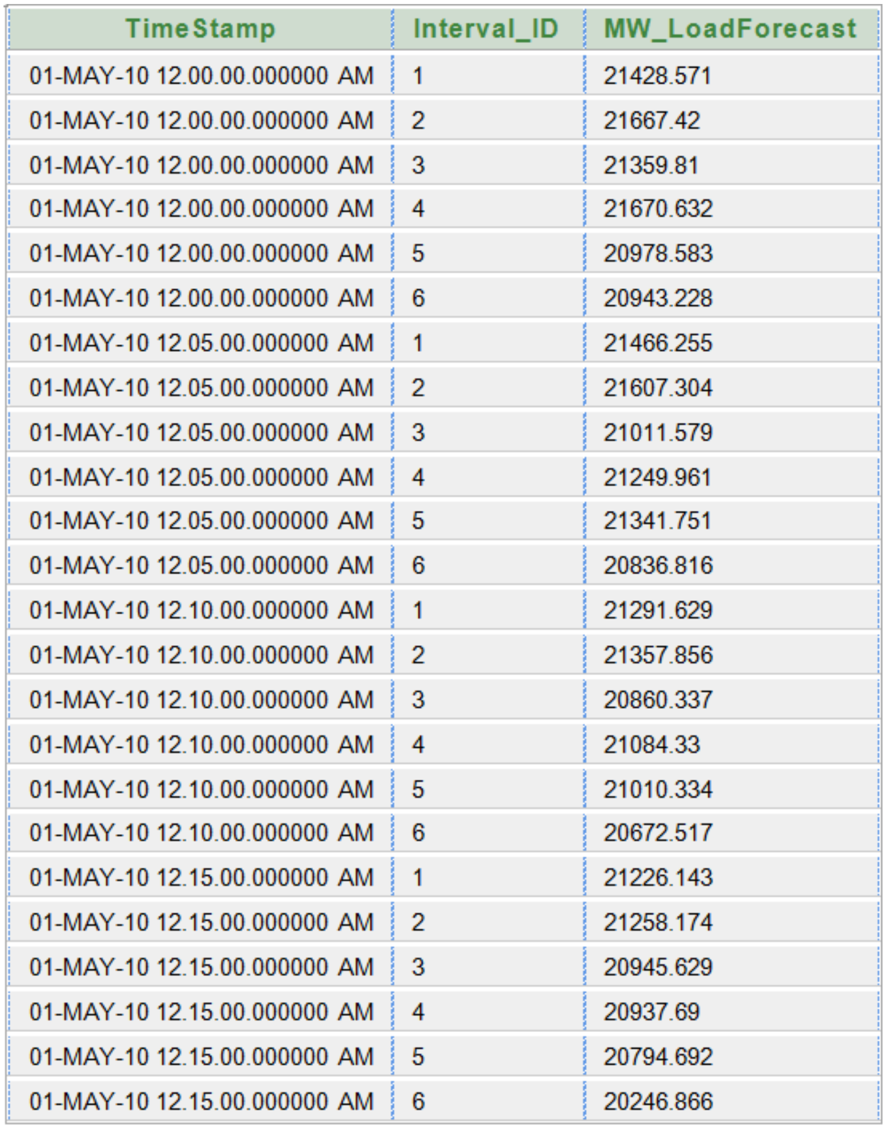


Table B.6. Data Sample - Real-Time Load Forecast



TimeStamp	Interval_ID	MW_LoadForecast
01-MAY-10 12.00.00.000000 AM	1	21428.571
01-MAY-10 12.00.00.000000 AM	2	21667.42
01-MAY-10 12.00.00.000000 AM	3	21359.81
01-MAY-10 12.00.00.000000 AM	4	21670.632
01-MAY-10 12.00.00.000000 AM	5	20978.583
01-MAY-10 12.00.00.000000 AM	6	20943.228
01-MAY-10 12.05.00.000000 AM	1	21466.255
01-MAY-10 12.05.00.000000 AM	2	21607.304
01-MAY-10 12.05.00.000000 AM	3	21011.579
01-MAY-10 12.05.00.000000 AM	4	21249.961
01-MAY-10 12.05.00.000000 AM	5	21341.751
01-MAY-10 12.05.00.000000 AM	6	20836.816
01-MAY-10 12.10.00.000000 AM	1	21291.629
01-MAY-10 12.10.00.000000 AM	2	21357.856
01-MAY-10 12.10.00.000000 AM	3	20860.337
01-MAY-10 12.10.00.000000 AM	4	21084.33
01-MAY-10 12.10.00.000000 AM	5	21010.334
01-MAY-10 12.10.00.000000 AM	6	20672.517
01-MAY-10 12.15.00.000000 AM	1	21226.143
01-MAY-10 12.15.00.000000 AM	2	21258.174
01-MAY-10 12.15.00.000000 AM	3	20945.629
01-MAY-10 12.15.00.000000 AM	4	20937.69
01-MAY-10 12.15.00.000000 AM	5	20794.692
01-MAY-10 12.15.00.000000 AM	6	20246.866

SQL script:

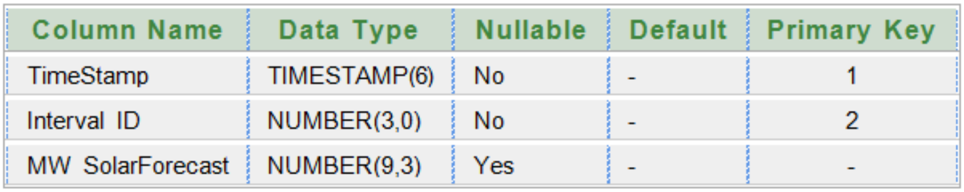
```
CREATE TABLE  "tblRealTimeLoadForecastTotal"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "Interval_ID" NUMBER(3,0),
   "MW_LoadForecast" NUMBER(9,3),
    CONSTRAINT "tblRealTimeLoadForecast_PK" PRIMARY KEY ("TimeStamp",
"Interval_ID") ENABLE
   )
```

Real-Time Solar Generation Forecast

Table Name = tblRealTimeSolarForecastTotal

Data Resolution = 5 min

Table B.7. Real-Time Solar Generation Forecast



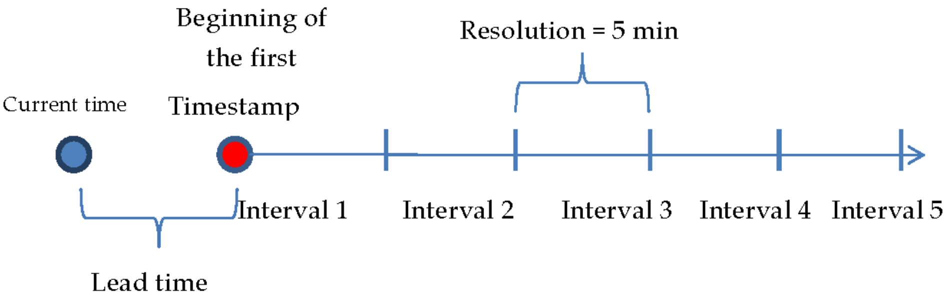
Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
Interval ID	NUMBER(3,0)	No	-	2
MW SolarForecast	NUMBER(9,3)	Yes	-	-

TimeStamp = timestamp – beginning of the first interval (!)

Interval_ID = interval ID - 5 min resolution, up to 13 intervals

MW_SolarForecast = real-time solar generation forecast (MW)

Figure B.2. Time and Resolution



SQL script:

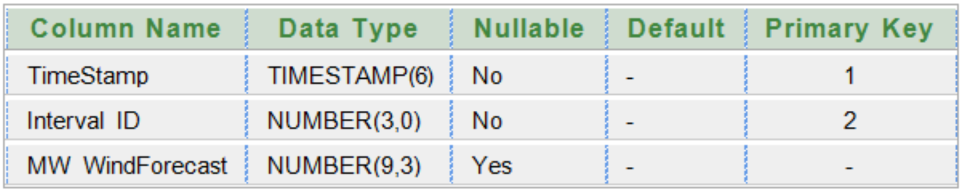
```
CREATE TABLE  "tblRealTimeSolarForecastTotal"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "Interval_ID" NUMBER(3,0),
   "MW_SolarForecast" NUMBER(9,3),
    CONSTRAINT "tblRealTimeSolarForecast_PK" PRIMARY KEY ("TimeStamp",
"Interval_ID") ENABLE
   )
```

Real-Time Wind Generation Forecast

Table Name = tblRealTimeWindForecastTotal

Data Resolution = 5 min

Table B.8. Real-Time Wind Generation Forecast



Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
Interval ID	NUMBER(3,0)	No	-	2
MW WindForecast	NUMBER(9,3)	Yes	-	-

TimeStamp = timestamp – beginning of the first interval (!)

Interval_ID = interval ID - 5 min resolution, up to 13 intervals

MW_WindForecast = real-time wind generation forecast (MW)

Figure B.3. Time and Resolution

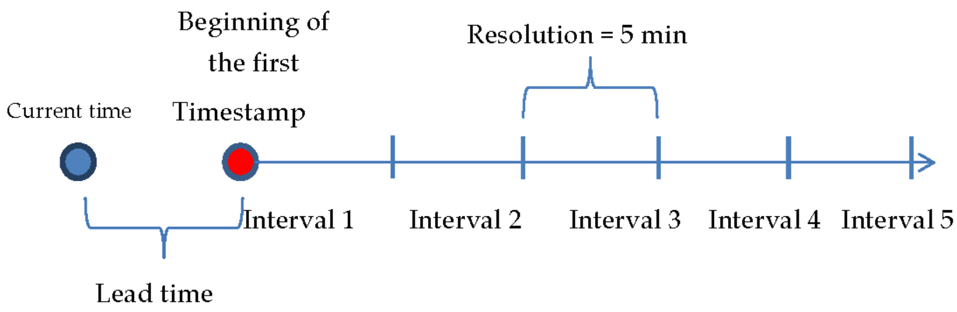
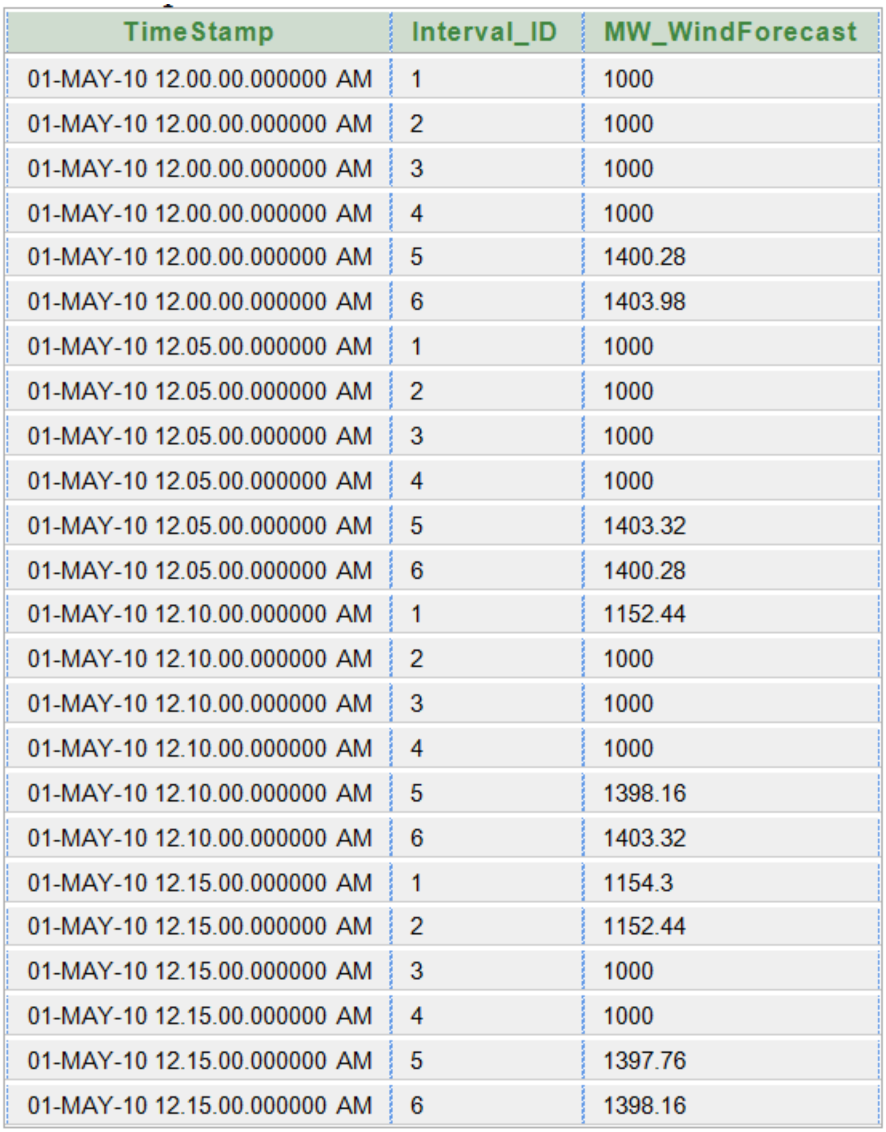


Table B.9. Data Sample - Real-Time Wind Generation Forecast



TimeStamp	Interval_ID	MW_WindForecast
01-MAY-10 12.00.00.000000 AM	1	1000
01-MAY-10 12.00.00.000000 AM	2	1000
01-MAY-10 12.00.00.000000 AM	3	1000
01-MAY-10 12.00.00.000000 AM	4	1000
01-MAY-10 12.00.00.000000 AM	5	1400.28
01-MAY-10 12.00.00.000000 AM	6	1403.98
01-MAY-10 12.05.00.000000 AM	1	1000
01-MAY-10 12.05.00.000000 AM	2	1000
01-MAY-10 12.05.00.000000 AM	3	1000
01-MAY-10 12.05.00.000000 AM	4	1000
01-MAY-10 12.05.00.000000 AM	5	1403.32
01-MAY-10 12.05.00.000000 AM	6	1400.28
01-MAY-10 12.10.00.000000 AM	1	1152.44
01-MAY-10 12.10.00.000000 AM	2	1000
01-MAY-10 12.10.00.000000 AM	3	1000
01-MAY-10 12.10.00.000000 AM	4	1000
01-MAY-10 12.10.00.000000 AM	5	1398.16
01-MAY-10 12.10.00.000000 AM	6	1403.32
01-MAY-10 12.15.00.000000 AM	1	1154.3
01-MAY-10 12.15.00.000000 AM	2	1152.44
01-MAY-10 12.15.00.000000 AM	3	1000
01-MAY-10 12.15.00.000000 AM	4	1000
01-MAY-10 12.15.00.000000 AM	5	1397.76
01-MAY-10 12.15.00.000000 AM	6	1398.16

SQL script:

```
CREATE TABLE  "tblRealTimeWindForecastTotal"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
```

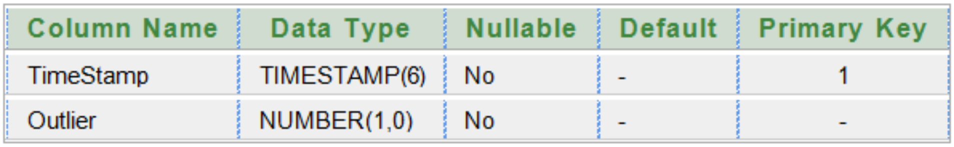
```
   "Interval_ID" NUMBER(3,0),
   "MW_WindForecast" NUMBER(9,3),
    CONSTRAINT "tblRealTimeWindForecast_PK" PRIMARY KEY ("TimeStamp",
"Interval_ID") ENABLE
   )
```

Outliers

Table Name = tblOutliers

Data Resolution = 1 min

Table B.10. Outliers



Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
Outlier	NUMBER(1,0)	No	-	-

TimeStamp = data point timestamp

Outlier = point is outlier (bad data):- True=1 or False=0

SQL script:

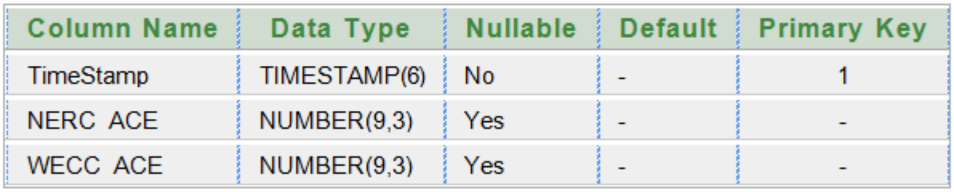
```
CREATE TABLE  "tblOutliers"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "Outlier" NUMBER(1,0) NOT NULL ENABLE,
    CHECK ("Outlier" IN ( '1', '0' )) ENABLE,
    CONSTRAINT "tblOutliers_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
```

Area Control Error (ACE)

Table Name = tblActualACE

Data Resolution = 1 min

Table B.11. Area Control Error (ACE)



Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
NERC ACE	NUMBER(9,3)	Yes	-	-
WECC ACE	NUMBER(9,3)	Yes	-	-

TimeStamp = data point timestamp

NERC_ACE = NERC ACE value (MW)

WECC_ACE = Raw ACE value (MW) (includes automatic time error correction component)

SQL script:

```
CREATE TABLE  "tblActualACE"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
        "NERC_ACE" NUMBER(9,3),
        "WECC_ACE" NUMBER(9,3),
```

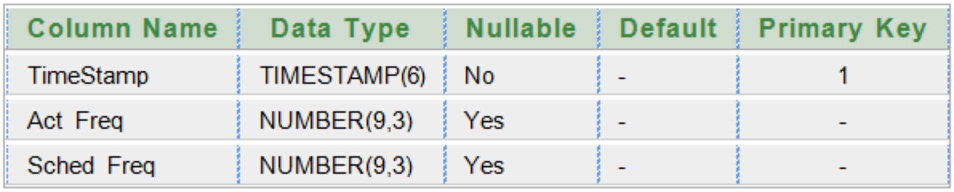
```
        CONSTRAINT "tblActualACE_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
```

Actual Frequency

Table Name = tblActualFrequency

Data Resolution = 1 min

Table B.12. Actual Frequency



Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
Act Freq	NUMBER(9,3)	Yes	-	-
Sched Freq	NUMBER(9,3)	Yes	-	-

TimeStamp = data point timestamp

Act_Freq= actual frequency value (Hz)

Sched_Freq = scheduled frequency value (Hz)

SQL script:

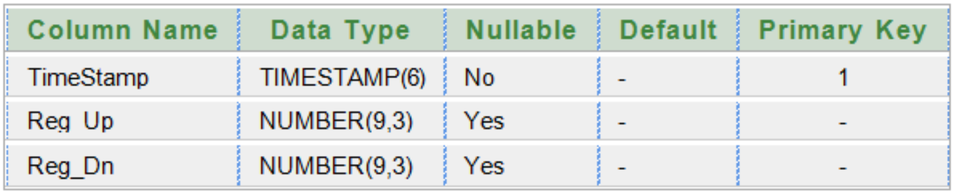
```
CREATE TABLE  "tblActualFrequency"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "Act_Freq" NUMBER(9,3),
   "Sched_Freq" NUMBER(9,3),
    CONSTRAINT "tblActualFreq_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
```

Actual Applied Regulation

Table Name = tblActualRegulation

Data Resolution = 1 min

Table B.13. Actual Applied Regulation



Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
Reg Up	NUMBER(9,3)	Yes	-	-
Reg_Dn	NUMBER(9,3)	Yes	-	-

TimeStamp = data point timestamp

Reg_Up= Regulation Up applied value (MW)

Reg_Dn = Regulation Down applied value (MW)

SQL script:

```
CREATE TABLE  "tblActualRegulation"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
        "Reg_Up" NUMBER(9,3),
```

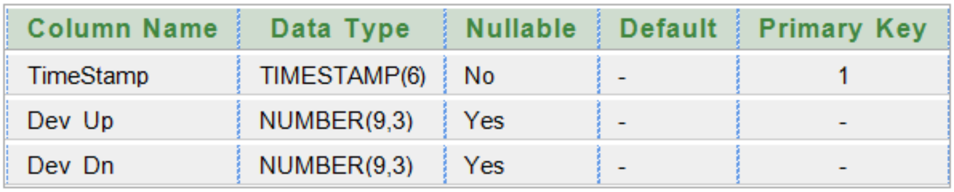
```
        "Reg_Dn" NUMBER(9,3),
         CONSTRAINT "tblActualReg_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
```

Uninstructed Units Deviation

Table Name = tblActualUnitsDeviation

Data Resolution = 1 min

Table B.14. Uninstructed Units Deviation



Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
Dev Up	NUMBER(9,3)	Yes	-	-
Dev Dn	NUMBER(9,3)	Yes	-	-

TimeStamp = data point timestamp

Dev_Up= conventional units total uninstructed deviation up value (MW)

Dev_Dn = conventional units total uninstructed deviation down value (MW)

SQL script:

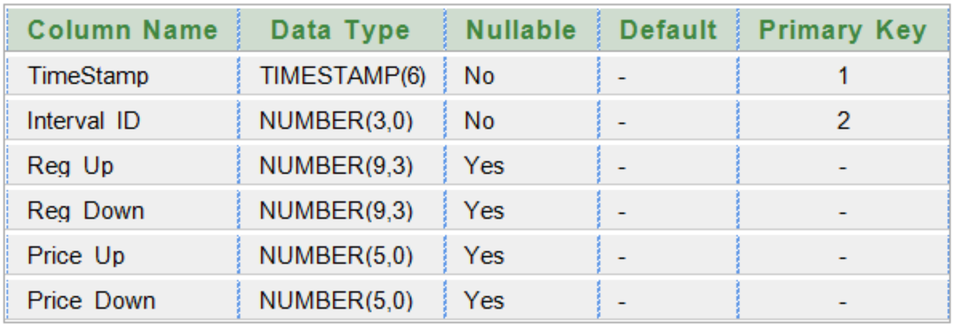
```
CREATE TABLE  "tblActualUnitsDeviation"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
        "Dev_Up" NUMBER(9,3),
        "Dev_Dn" NUMBER(9,3),
         CONSTRAINT "tblActualUnitsDev_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
```

Day-Ahead Regulation Procurement

Table Name = tblDayAheadRegProcurement

Data Resolution = 1h

Table B.15. Day-Ahead Regulation Procurement



Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
Interval ID	NUMBER(3,0)	No	-	2
Reg Up	NUMBER(9,3)	Yes	-	-
Reg Down	NUMBER(9,3)	Yes	-	-
Price Up	NUMBER(5,0)	Yes	-	-
Price Down	NUMBER(5,0)	Yes	-	-

TimeStamp = date only (!)

Interval_ID = interval ID (Hour Ending)

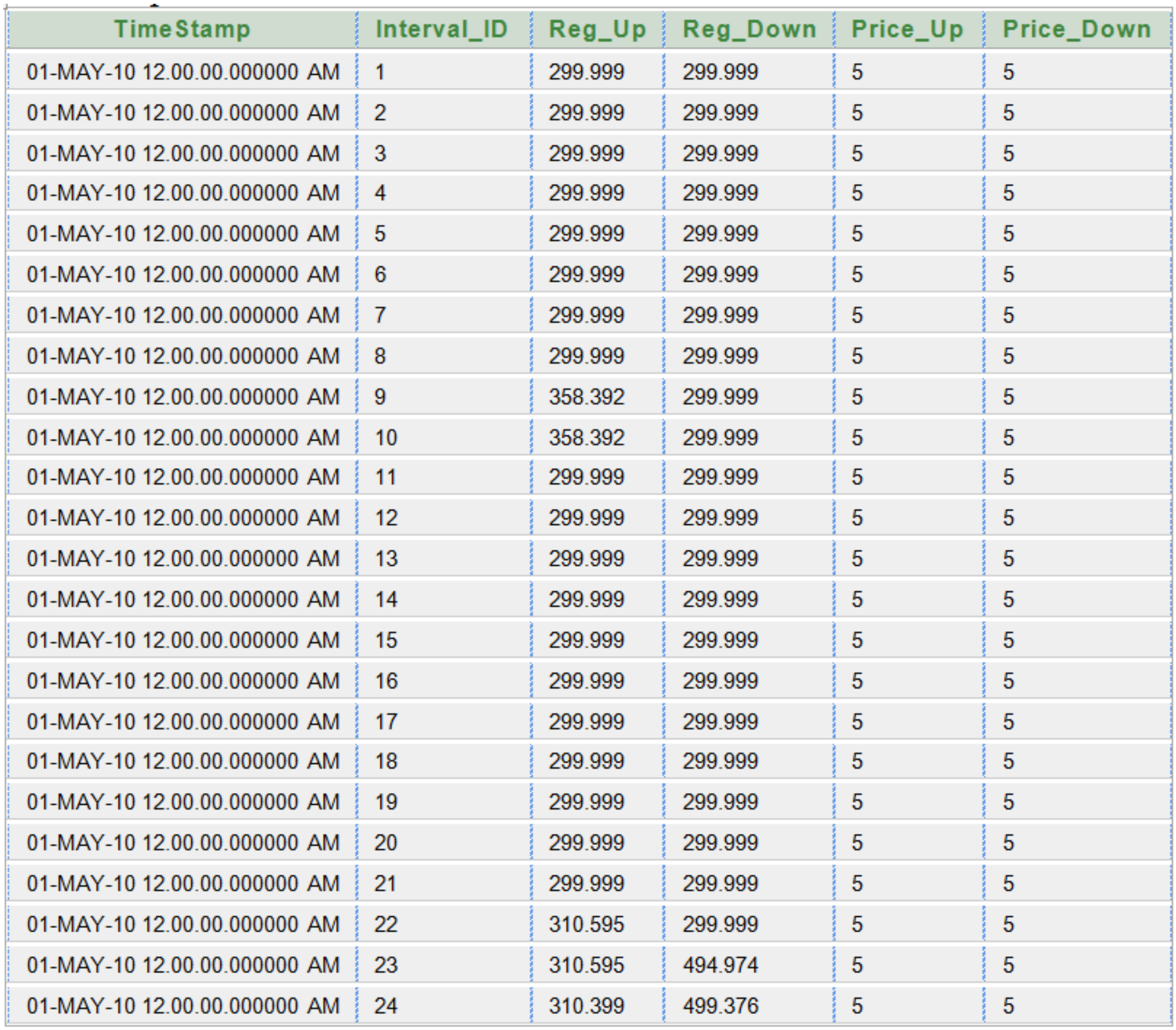
Reg_Up = day-ahead regulation up procurement (MW)

Reg_Down = day-ahead regulation down procurement (MW)

Price_Up = day-ahead regulation up price ($/MW)

Price_Down = day-ahead regulation down price ($/MW)

Table B.16. Data Sample - Day-Ahead Regulation Procurement



TimeStamp	Interval_ID	Reg_Up	Reg_Down	Price_Up	Price_Down
01-MAY-10 12.00.00.000000 AM	1	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	2	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	3	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	4	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	5	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	6	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	7	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	8	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	9	358.392	299.999	5	5
01-MAY-10 12.00.00.000000 AM	10	358.392	299.999	5	5
01-MAY-10 12.00.00.000000 AM	11	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	12	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	13	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	14	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	15	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	16	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	17	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	18	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	19	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	20	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	21	299.999	299.999	5	5
01-MAY-10 12.00.00.000000 AM	22	310.595	299.999	5	5
01-MAY-10 12.00.00.000000 AM	23	310.595	494.974	5	5
01-MAY-10 12.00.00.000000 AM	24	310.399	499.376	5	5

SQL script:

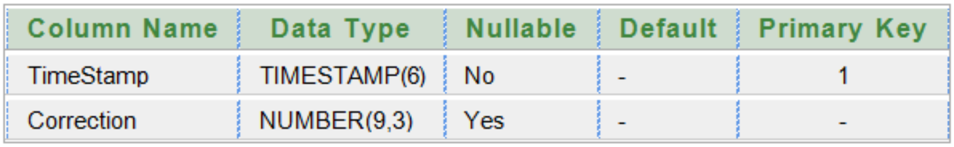
```
CREATE TABLE  "tblDayAheadRegProcurement"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
        "Interval_ID" NUMBER(3,0),
        "Reg_Up" NUMBER(9,3),
        "Reg_Down" NUMBER(9,3),
        "Price_Up" NUMBER(5,0),
        "Price_Down" NUMBER(5,0),
         CONSTRAINT "tblDayAheadRegProcurement_PK" PRIMARY KEY ("TimeStamp",
"Interval_ID") ENABLE
   )
```

Automatic Time Error Correction

Table Name = tblTimeErrorCorrection

Data Resolution = 1 min

Table B.17. Automatic Time Error Correction

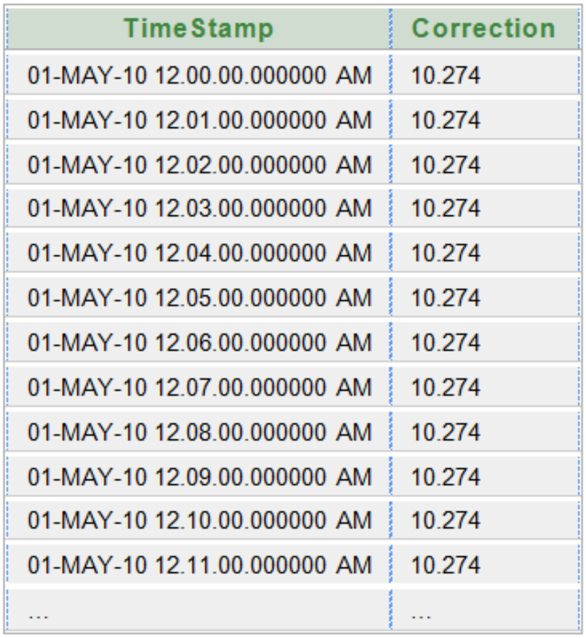


Column Name	Data Type	Nullable	Default	Primary Key
TimeStamp	TIMESTAMP(6)	No	-	1
Correction	NUMBER(9,3)	Yes	-	-

TimeStamp = data point timestamp

Correction= time error correction value (MW)

Table B.18. Data Sample - Automatic Time Error Correction



TimeStamp	Correction
01-MAY-10 12.00.00.000000 AM	10.274
01-MAY-10 12.01.00.000000 AM	10.274
01-MAY-10 12.02.00.000000 AM	10.274
01-MAY-10 12.03.00.000000 AM	10.274
01-MAY-10 12.04.00.000000 AM	10.274
01-MAY-10 12.05.00.000000 AM	10.274
01-MAY-10 12.06.00.000000 AM	10.274
01-MAY-10 12.07.00.000000 AM	10.274
01-MAY-10 12.08.00.000000 AM	10.274
01-MAY-10 12.09.00.000000 AM	10.274
01-MAY-10 12.10.00.000000 AM	10.274
01-MAY-10 12.11.00.000000 AM	10.274
...	...

SQL script:

```
CREATE TABLE  "tblTimeErrorCorrection"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "Correction" NUMBER(9,3),
    CONSTRAINT "tblTimeErrorCorrection_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
```

Database Schema

```
CREATE TABLE  "tblActualACE"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "NERC_ACE" NUMBER(9,3),
   "WECC_ACE" NUMBER(9,3),
```

```
    CONSTRAINT "tblActualACE_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
/
CREATE TABLE  "tblActualFrequency"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "Act_Freq" NUMBER(9,3),
   "Sched_Freq" NUMBER(9,3),
    CONSTRAINT "tblActualFreq_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
/
CREATE TABLE  "tblActualInterchangeTotal"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "MW_Interchange" NUMBER(9,3),
    CONSTRAINT "tblActualInterchangeTotal_PK" PRIMARY KEY ("TimeStamp")
ENABLE
   )
/
CREATE TABLE  "tblActualLoadTotal"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "MW_ActualLoad" NUMBER(9,3),
    CONSTRAINT "tblActualLoadTotal_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
/
CREATE TABLE  "tblActualRegulation"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "Reg_Up" NUMBER(9,3),
   "Reg_Dn" NUMBER(9,3),
    CONSTRAINT "tblActualReg_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
/
CREATE TABLE  "tblActualSolarTotal"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "MW_ActualSolar" NUMBER(9,3),
    CONSTRAINT "tblActualSolarTotal_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
/
CREATE TABLE  "tblActualUnitsDeviation"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "Dev_Up" NUMBER(9,3),
   "Dev_Dn" NUMBER(9,3),
    CONSTRAINT "tblActualUnitsDev_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
/
CREATE TABLE  "tblActualWindTotal"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "MW_ActualWind" NUMBER(9,3),
    CONSTRAINT "tblActualWindTotal_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
/
CREATE TABLE  "tblOutliers"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "Outlier" NUMBER(1,0) NOT NULL ENABLE,
    CHECK ("Outlier" IN ( '1', '0' )) ENABLE,
    CONSTRAINT "tblOutliers_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
/
CREATE TABLE  "tblRealTimeLoadForecastTotal"
```

```
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "Interval_ID" NUMBER(3,0),
   "MW_LoadForecast" NUMBER(9,3),
    CONSTRAINT "tblRealTimeLoadForecast_PK" PRIMARY KEY ("TimeStamp",
"Interval_ID") ENABLE
   )
/
CREATE TABLE  "tblRealTimeSolarForecastTotal"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "Interval_ID" NUMBER(3,0),
   "MW_SolarForecast" NUMBER(9,3),
    CONSTRAINT "tblRealTimeSolarForecast_PK" PRIMARY KEY ("TimeStamp",
"Interval_ID") ENABLE
   )
/
CREATE TABLE  "tblRealTimeWindForecastTotal"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "Interval_ID" NUMBER(3,0),
   "MW_WindForecast" NUMBER(9,3),
    CONSTRAINT "tblRealTimeWindForecast_PK" PRIMARY KEY ("TimeStamp",
"Interval_ID") ENABLE
   )
/
/
CREATE TABLE  "tblTimeErrorCorrection"
   (    "TimeStamp" TIMESTAMP (6) NOT NULL ENABLE,
   "Correction" NUMBER(9,3),
    CONSTRAINT "tblTimeErrorCorrection_PK" PRIMARY KEY ("TimeStamp") ENABLE
   )
/
```