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Operational Impacts of Wind Energy Resources in the Bonneville Power Administration Control Area – Phase I Report

YV Makarov
S Lu

May 2008

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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SUMMARY

Wind power is growing at a very fast pace as an alternative generating resource. As the share of wind power in the total system generation capacity increases, the impact of wind power on various aspects of power systems becomes more significant. This report presents a methodology developed to study the future impact of wind power on Bonneville Power Administration (BPA) load following and regulation requirements as well as study results obtained using this methodology in the course of collaborative work between BPA and Pacific Northwest National Laboratory (PNNL). The methodology has the following features that make it more accurate, more trustworthy, and more flexible comparing to some other existing approaches:

- PNNL's methodology simulates the actual BPA balancing process by mimicking essential details of the actual scheduling and regulation processes.
- The approach considers statistical interactions between the wind forecast (wind scheduling) error and the load forecast error.
- The methodology used in this study provides not only capacity requirement information, it also analyzes the ramp rate requirements for system load following and regulation processes.
- The inherent relationship between the required load following and regulation capacity, ramping capability, and ramp duration is fully reflected in the methodology.
- The methodology simulates the load and wind forecast error based on their historically observed statistical characteristics. The truncated normal probability distribution model with autocorrelation was used to simulate these errors.
- The intra-hour load following requirements caused by the differences between the block hourly energy schedules and the continuously changing system balance requirements are replicated in the proposed technique.
- The percentile approach used in the analysis helps to determine requirements that are needed for a robust the load following and regulation processes without overdoing the job.
- The methodology is flexible enough to incorporate changes in BPA's balancing process. This allows analyzing incremental changes associated with these changes.

Algorithms and MATLAB codes were developed to implement the methodology. The MATLAB codes as well as the datasets used in the study are attached to this report.

The load following and regulation capacity and ramp requirements have been studied for the following cases, using the existing or projected wind installation capacity in BPA system from year 2006 through year 2010:

- 1) Load and wind forecast error included, load following process included, and 10-minute load following time interval;
- 2) Load and wind forecast error not included, load following process included, 10-minute load following time interval;

- 3) Load and wind forecast error not included, load following process included, 15-minute load following time interval;
- 4) Load and wind forecast error not included, load following process not included (only regulation process exists for system balancing need).

The main findings are (the requirements mentioned below include both capacity and ramp requirements):

- The reserve requirements for regulation process when no load following process exists are approximately the sum of load following and regulation requirements when there is a load following process.
- Shorter load following interval (10 minutes) results in smaller regulation requirements than a longer load following interval (15 minutes), while the load following requirements in both cases are approximately the same.
- Forecast errors on wind and load increase the load following and regulation requirements, sometimes dramatically (1500 MW difference has been seen in the 2010 case. However, this type of events is infrequent and therefore is removed as outliers and not shown in the result figures).
- Load following requirements increased by wind are much more than the increase on regulation requirements: in case 3), for assumed wind power capacity of 6300 MW in 2010, the maximum increase for load following capacity is 400 MW Up and 500 MW Down vs. 90 MW Up and 60 MW Down for regulation capacity.
- The distribution of load following and regulation requirements is not normal. It has long tails along the capacity or ramp axis, which means there are infrequent occasions that the system needs very high capacity and ramp capability for balancing processes. The tail events are usually the results of high wind and load ramps superposed on forecast errors.

Results of the study have been disseminated worldwide. Papers have been presented at the IEEE Transmission and Distribution Conference (Chicago, IL, 2008), 7th Large Scale Wind Integration Workshop in Madrid, Spain (2008), European Energy Market Conference in Lisbon, Portugal (2008), and Windpower 2008 Conference and Exhibition (Houston, TX). The methodology was also used in a recent study conducted by PNNL for the California Independent System Operator (California ISO).

We recommend the following actions for BPA to effectively manage the operational impacts of wind:

- Evaluate the need in both capacity and ramp capability for load following and regulation services at projected wind penetration levels in future years.
- Evaluate the capacity and ramp capability of BPA's existing generation resources that can be used in the load following and regulation processes. Ensure the adequacy of system balancing resources.
- Develop a market mechanism to encourage more generating resources or other flexible resources such as energy storage and demand response to participate in the balancing

processes. This will help reducing the balancing obligations on the already very constrained BPA hydro system and potentially lower the balancing cost.

- Incorporate wind forecast into day ahead scheduling and real-time scheduling processes to reduce the need for reserves.

- Develop a mechanism to encourage wind power plants to stay with their schedules (based on forecasts).

- Analyzing the frequency, severity and consequences of tail events in the BPA system and build strategies to deal with tail events.

We recommend doing the following in Phase II to improve the methodology and the accuracy and robustness of the study results:

- Improving the credibility of data sets, especially future wind data.

- Randomization of the study using Monte Carlo simulation approach, which includes:
  - The use of 3 years of the actual load data to capture the variability characteristics;
  - Use randomly generated wind generation forecast errors to produce wind generation schedules (based on certain probability distribution characteristic and autocorrelation between the subsequent forecasts; this information can be calculated based on the 3Tier historical data);
  - Similarly, use randomly generated load-forecast errors to produce load schedules. Note that in Phase I study we just used scaled-up 2006 load schedules.

- Discuss with other industry experts to validate the methodology.

- Investigate and summarize the world experience on analyzing and mitigating the operational impacts of wind integration.

CONTENTS

FIGURES

1.0 INTRODUCTION

The Bonneville Power Administration (BPA) is a federal power marketing agency, which owns 75% of high voltage transmission and markets 40% of the electric power in the Pacific Northwest region. BPA is currently purchasing power from five wind farms, the total capacity of which is close to 1,000 MW [2]. Figure 1 shows one of the scenarios for the projected wind installation capacity additions in the BPA system until 2010 [3].

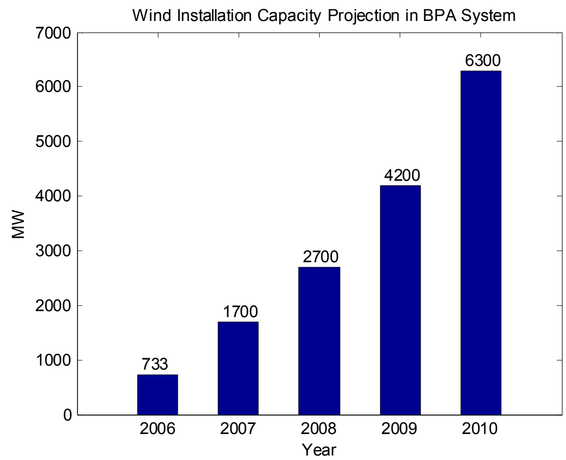

Figure 1. Wind installation capacity projection in the BPA power system (as of April 2007)

As a result of wind's variability and forecast uncertainties, a large scale integration of wind energy can impact power system reliability, operating efficiency, power quality and other aspects [4]. As wind penetration rate increases, these impacts become more significant. The power system may have to increase its capacity and flexibility in both generation and transmission to accommodate the increasing production of wind energy. Appropriate changes to system operations may be required as well. In the Department of Energy (DOE's) wind-grid integration effort, three directions have been pointed out for research: (1) development of wind turbine generator models and wind plant performance data; (2) tools and methods development for assessing ancillary service, system impact and capacity credit; and (3) application and implementation strategies based on the actual performance of wind plants to increase wind energy deployment [5].

This report presents the methodology that Pacific Northwest National Laboratory (PNNL) developed for BPA to assess the incremental needs of ancillary services, in particular, load following and regulation, required for the integration of wind energy. Regulation is to follow minute-by-minute variations of load, while load following is the real-time dispatch to compensate for intra-hour variation of load (with a dispatch interval between 5 and 15 minutes).

Wind impact on system operations over multi-hour time scale is also an important issue, but is out of the scope of this study. A multitude of utilities and organizations have analyzed the wind integration issues, and a summary of both the methodologies and the results is provided by Parsons et al. in [6]. These methodologies can be categorized into two groups: detailed dispatch model simulations, as in Xcel Energy and Electrotek Concepts [7]-[8], and standard deviation analysis on load and wind data to quantify variability, as in Hirst, EnerNet, and Holttinen [9]-[11]. Dispatch modeling tools have only limited capability to simulate wind variability in different time scales and are difficult to incorporate wind forecast errors [6], [12]. Standard deviation based analysis on wind and load data does not take into consideration actual operational practices of a control area. The separation of load-following and regulation requirements in this methodology is based on the moving average approach which is artificial. Results would be more realistic if the actual system operation procedures were taken into consideration. The methodology developed by PNNL for this study overcomes the drawbacks of both existing methodologies. It uses historical data and stochastic processes to simulate the load balancing processes in the BPA power system. Then capacity, ramp rate and ramp duration characteristics are extracted from the simulation results. The ancillary service capacity requirements are generated accordingly. The methodology mimics the actual power system operations so that the results can be more accurate than standard deviation based approach, and more convenient and less time consuming than the dispatch model simulation approach. Further, the ramp rate and ramp duration data obtained from the analysis can be used to evaluate generator response or maneuverability and energy requirement, respectively, in addition to the capacity requirements. This methodology was applied to the BPA power system data and the results were aligned with BPA operational experience. It provides a convenient yet powerful approach to evaluate the impact of wind on system ancillary services.

This report is organized as follows:

- Section II briefly describes BPA practice for load and generation balancing processes;
- Section III explains how to generate the data sets used in the study;
- Section IV describes the methodology developed for the study;
- Section V presents the wind impact study results for the BPA power system;
- Section VI is the study conclusions and recommendations for improvements;
- Section VII contains references.
- Appendix I is a summary of data preparation and simulation procedures of the methodology;
- Appendix II describes an approach to generate random series in truncated normal distribution (TND) with autocorrelation. The random series are used to simulate forecast errors in the proposed methodology;
- Appendix III discusses an issue related to the removal of extreme events from study results;
- Appendix IV shows the study results when wind and load forecast errors are considered;
- Appendix V shows the study results when forecast errors are not considered.

2.0 BPA PRACTICE FOR LOAD AND GENERATION BALANCING PROCESSES

Determining the impact of wind on ancillary services is mostly focused on assessing the system load following and regulation requirements for the load-balancing processes. The results should closely depend on the load-balancing practice of a control area. Therefore, BPA system practice is briefly described in the following [13].

Fig. 2 shows the timeline of BPA scheduling procedures. The BPA generation scheduling process is based on bulk hourly energy schedules and includes 20-minute ramps between the hours (beginning 10 minutes before the end of an hour and ending 10 minutes after the beginning of an hour). Pre-schedule is based on day-ahead forecast and completed before 2 p.m. the day before the day-of-delivery. Real-time schedule is based on hour-ahead forecast completed 20 minutes before the hour-of-delivery and implemented by adjusting generation units' base point settings.

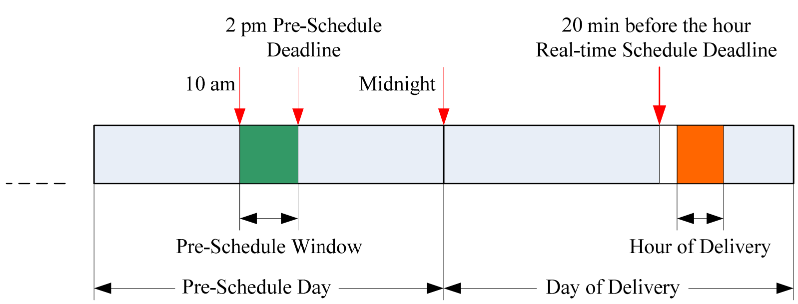

Figure 2. BPA scheduling procedure

There is not a within-hour/real-time scheduling process, or load following, presently existing in the BPA system. Load following in the BPA system may be interpreted as the process of manual adjustment of the generation base points when deviation of the regulating units from their base points exceeds certain thresholds. This adjustment can be repeated every 30 minutes by BPA real-time dispatches, if needed.

To reduce system regulation capacity requirements, a within-hour scheduling process, with 10-min interval, is being considered for the BPA power system in the future. This process is simulated to study the future impact of wind on the BPA system.

Regulation service, which follows the moment-to-moment changes of load, is accomplished by committing on-line generators responding to automatic generating control (AGC) signals every 4 seconds. The outputs of these generators are raised or lowered based on the difference between generation schedule and actual load.

3.0 DATA SET GENERATION

Data needed in the study include BPA system total generation, load and wind data for an entire year. In the analysis, the scheduled interchange component in the generation schedule was not considered. The generation schedule to meet internal system load (i.e., not including interchange) was assumed to be the same as load forecast minus wind generation forecast, and there was no deviation of actual generation from its schedule (called generation imbalance or GI. GI can be included in the study if it is a concern.) With these assumptions, the regulation and load-following requirements can be derived using the following data sets: actual load, load forecast, actual wind and wind forecast.

For a detailed data sets specification used in the study, please refer to Appendix I.

3.1 Actual Load

The actual load of year 2006 is BPA historical data with 1-minute resolution. Although the AGC signal adjusting regulating units has a 4-second periodicity, generators normally are not expected to respond to its change that fast (except for some fast regulating resources such as the flywheel or battery energy storage, but these units are still very rare). The response time to AGC signals is limited by the actual ramping capability of the units on regulation. Therefore, it is considered adequate to use 1-minute averages in analyzing the effect of regulation.

For a future study year 2006+*i*, the annual actual load curve can be simulated as the year 2006 load multiplied by the *i*-th power of the annual load growth factor γ ($\gamma > 1$).

3.2 Load Forecast

The hour-ahead forecast can be simulated using the following procedure:

(1) Generate the hourly average of actual load using historical load data and calculate the hourly average of the actual load for each study hour.

(2) Generate forecast errors using a random series with truncated normal distribution (TND) with autocorrelation for each hour;

(3) Subtract forecast errors simulated in (2) from the average actual load determine in (1) and the resulting curve will be used as hour-ahead load forecast and block energy schedule;

(4) Add 20 minutes inter-hour ramps to the load block energy schedule from (3), mimicking a component of the actual BPA generation schedule that corresponds to system load.

In step (2), a truncated normal distribution (TND) is used because in normal distribution the range of data values is infinite, which is certainly not true for forecast errors. The probability density function (PDF) of the TND is expressed by the following formula:

$$PDF_{TND}(\varepsilon) = \begin{cases} 0, & -\infty \le \varepsilon < \varepsilon_{\min} \\ \dfrac{PDF_N(\varepsilon)}{\int_{\varepsilon_{\min}}^{\varepsilon_{\max}} PDF_N(\varepsilon) d\varepsilon}, & \varepsilon_{\min} \le \varepsilon \le \varepsilon_{\max} \\ 0, & \varepsilon_{\max} \le \varepsilon \le +\infty \end{cases} \tag{1}$$

where $PDF_N(\varepsilon)$ is the PDF of the normal distribution:

$$PDF_N(\varepsilon) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}\left(\frac{\varepsilon-\varepsilon_0}{\sigma}\right)^2}, \ -\infty \le \varepsilon \le +\infty \tag{2}$$

Figure 3 illustrates the PDF of a TND series.

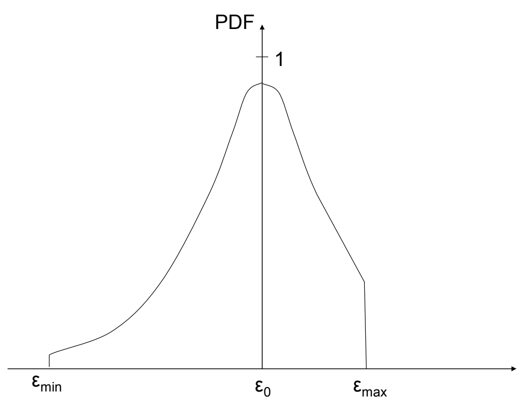

Figure 3. PDF of Truncated Normal Distribution

Parameters of TND, such as mean ε_0, standard deviation σ, maximum error $\varepsilon_{\max}$ and minimum error $\varepsilon_{\min}$ should be consistent with the statistical features of the actual forecast. Autocorrelation is applied when generating the random series because studies on the historical forecast data show a significant correlation between the errors on neighboring data points. An approach to generate a data series in TND with autocorrelation is described in Appendix II.

The procedure (1) to (4) is especially useful when historical data for load forecast is not available, or an hourly load forecast with specified statistical characteristics is of interest.

Now we have obtained hour-ahead forecast data to simulate the hourly schedule. Next, real-time forecast data with 10-min interval is needed to simulate the real-time schedule, i.e., load-following process. It can be generated using the same four-step procedure for hour-ahead forecast data described above. The difference is on the forecast interval and ramp length between two forecast data points. In the simulations for the BPA system, a 10-min interval and a 10-min ramp length are used.

Figure 4 shows an example of the hour-ahead and 10-min real-time forecasts data generated using the procedure described above.

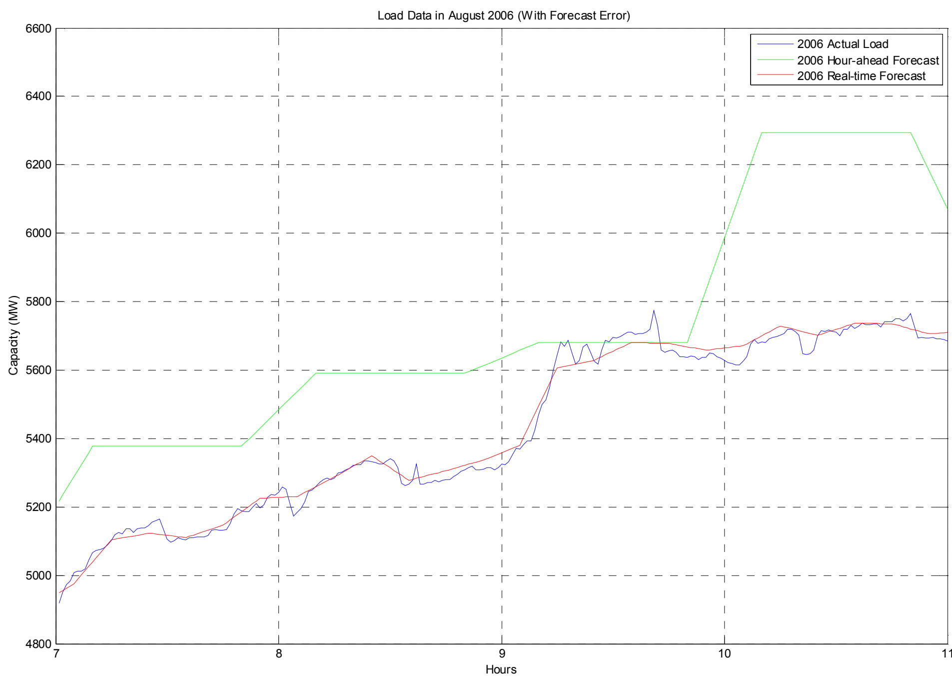

Figure 4. Forecast data example

3.3 Actual Wind

"Actual" wind data from 2006 to 2010 was provided by BPA. Wind data from 2006 was generated using a combination of 3Tier Company's Mesoscale Model and actual wind farm data [3]. Wind data of future years was expanded from 2006 data, using a capacity coefficient and a delay to count for location difference. This approach is a quick solution to generate future wind data and is certainly not perfect. Better approaches are being developed and will be applied once available.

3.4 Wind Forecast

Hour-ahead wind forecast data is generated using a wind forecast formula provided by BPA. Real-time 10-min interval wind forecast data is generated using the naïve persistence model, which assumes that the wind generation is the same as what it was a certain amount of minutes ago.

If the wind forecast data is not available or the persistence model is not preferred, the same approach used to generate load forecast data, as described in B, can also be applied to wind data. The statistical characteristics of wind forecast error, including mean, standard deviation, max and min values must be specified, as well as the correlation value of forecast error between neighboring points.

Because statistical processes are involved in the data set generation work, Monte Carlo simulations on forecast errors were used to ensure the results are representative in most cases. Actual load and wind data should also be varied according to their actual characteristics to conduct multiple simulation runs, but this has not yet been done in this study.

4.0 METHODOLOGY TO EVALUATE LOAD-FOLLOWING AND REGULATION REQUIREMENTS

Various approaches have been utilized in the evaluation of additional regulation and load-following capacity needed by the integration of wind energy. The dispatch model simulation approach is limited by the capability of the dispatch tool and usually can not conveniently simulate load following and regulation processes. In the standard deviation evaluation approach, the variability of load and wind is assessed after the data sets are processed with a moving average filter. It is essentially assuming the generation can follow the trend (moving average) of load precisely minute-by-minute. Therefore, it does not accurately represent the actual power system balancing processes. The methodology developed in this study overcomes the drawbacks of these two approaches, as well as provides additional capability to evaluate generator maneuverability and energy requirement.

4.1 Expressing the Regulation and Load-Following Requirements through the Simplified Area Control Error (ACE) Equation

The power system control objective is to minimize its control area ACE in the extent sufficient to comply with the North American Electric Reliability Corporation (NERC) Control Performance Standards (CPS). Therefore, the "ideal" regulation/load following signal is the signal that opposes deviations of ACE from zero when they exceed certain threshold:

$$\begin{aligned} -ACE &= -(I_a - I_s) + 10B(F_a - F_s) \\ &\approx -(G_a - L_a) \rightarrow \min \end{aligned} \tag{3}$$

where subscript *a* denotes actual, *s* denotes schedule, *I* stands for interchange between control areas, *F* stands for system frequency, and B is the system frequency bias (MW/0.1Hz, a negative value). G_a is the actual generation to serve load within the control area, and L_a is the actual load within the control area.

We then extend the generation component in the simplified ACE equation as

$$G_a = G_s + G_{lf} + G_r \tag{4}$$

where subscript *s* refers to hour-ahead schedule, *lf* refers to generation involved in the load-following process, and *r* refers to generation involved in the regulation process.

Based on our assumptions that generation schedule is equal to load forecast, we have

$$G_s = L_{f\_ha} \tag{5}$$

where L_{f_ha} is hour-ahead load forecast.

Let ACE be equal to zero, then we can separate load following and regulation as follows:

$$G_{lf} = L_{f\_rt} - L_{f\_ha} \tag{6}$$

$$G_r = L_a - L_{f\_rt} \tag{7}$$

where L_{f_rt} is real-time load forecast, and L_a is actual load.

When wind generation is included, we count wind as negative load. Therefore, similar to the situation without wind, we have:

$$G_s = L_{f\_ha} - G^w_{f\_ha} \tag{8}$$

$$G_{lf} = (L_{f\_rt} - G^w_{f\_rt}) - (L_{f\_ha} - G^w_{f\_ha}) \tag{9}$$

$$G_r = (L_a - G^w_a) - (L_{f\_rt} - G^w_{f\_rt}) \tag{10}$$

Figure 5 illustrates the approach of separating load following and regulation processes.

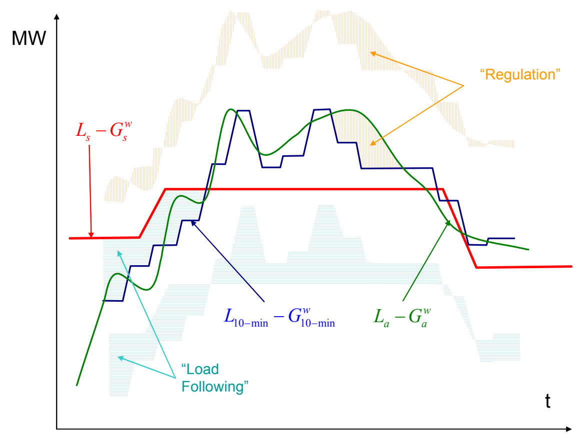

Figure 5. Separation of regulation and load following based on real-time forecast

4.2 Assessment of Ancillary Service Requirements

After the load-following and regulation data are obtained using formulas in A, the data are then processed to obtain the triple (capacity, ramp rate, ramp duration) for each data point. Figure 6 illustrates the concept of ramp rate and ramp duration. In Figure 6, π represents capacity, ρ represents ramp rate, and δ represents ramp duration. Based on the analysis illustrated in Figure 6, we conclude that points 1, 2, and 3 correspond to different magnitudes π_1, π_2 and π_3, whereas the ramping requirement at all these points is the same $\rho_{1\text{-}3}$.

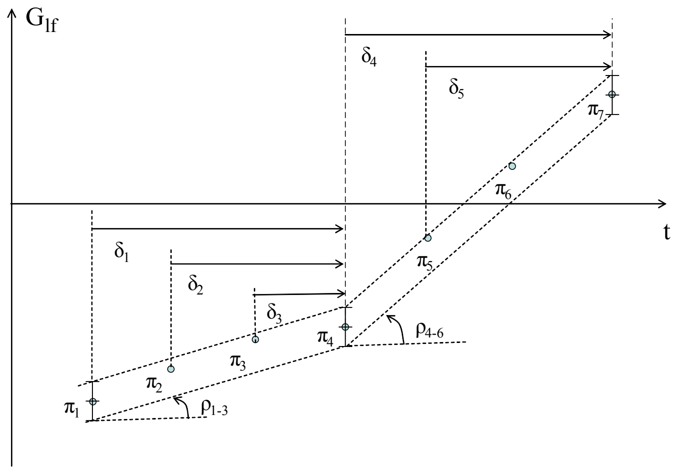

Figure 6. Obtaining capacity, ramp rate, and ramp duration characteristics

The regulating unit ramping capability can directly influence the required amount of regulation. If the ramping capability is insufficient, more units and more capacity must be involved in regulation to follow the ramps. Therefore, the ramping requirements for the integration of wind energy are necessary to study and quantify.

Another characteristic derived from the ancillary service data is “ramp duration”. It may be used to evaluate the adequacy of energy of the units participating regulation and load-following services. The energy requirement becomes important when resources with limited energy are involved in regulation, such as the flywheel energy storage devices. A limited energy capability will also influence the regulation capacity requirement.

4.3 Concurrent Statistical Analysis of the Regulation and Load-Following Requirements

When evaluating the requirements, a percentage of data points which are located at the boundaries (extreme cases) of the data distribution region in the three-dimensional space (capacity π, ramp rate ρ, ramp duration δ) are excluded. Figure 7 is an illustration of this step. The points inside the box (N_{in}) are included, while the points outside the box (N_{out}) are excluded. If a point is excluded, the regulation or load-following requirements are not met at that point. This approach helps to determine the probability of being outside the box, which is

$$p_{out} = \frac{N_{out}}{N_{out} + N_{in}} \tag{11}$$

The percentage of excluded data p_{out} is equally applied to each of the three dimensions: capacity, ramp rate and ramp duration. This corresponds to the fact that the NERC standards do not require ACE to be controlled 100% of the time. At the same time, the impact of outliers in the data is largely reduced through this procedure.

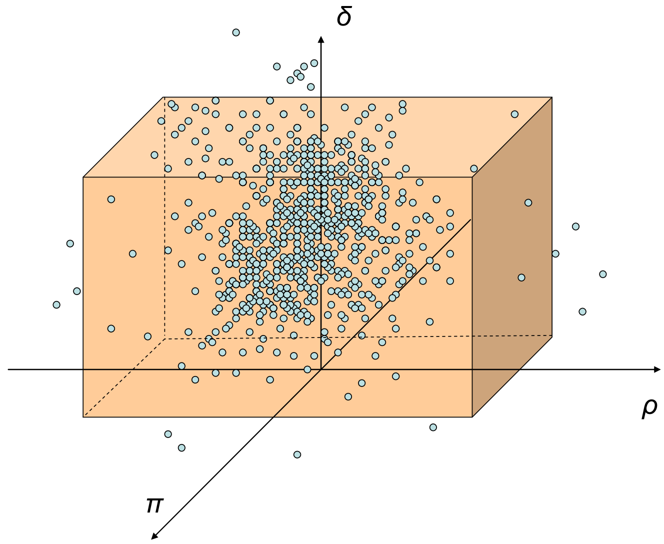

Figure 7. **Concurrent consideration of the capacity, ramping and duration requirements**

One thing worth mentioning in this step is at which time the extreme cases are excluded. There are two options: (1) remove them month by month or (2) remove them hour by hour. Because the distribution of data are different in each hour, and distribution of hourly data is different from monthly data, the above two approaches give different results. Which option to choose depends on the goal of reliability level and control performance the control area sets to achieve. For a detailed discussion, please see Appendix III.

The results shown in this report were generated using option (1).

5.0 BPA SYSTEM STUDY RESULTS

The load following and regulation capacity and ramp requirements have been studied for the following cases, using the existing or projected wind installation capacity in BPA system from year 2006 through year 2010:

- 1) Load and wind forecast error included, load following process included, and 10-minute load following time interval;
- 2) Load and wind forecast error not included, load following process included, 10-minute load following time interval;
- 3) Load and wind forecast error not included, load following process included, 15-minute load following time interval;
- 4) Load and wind forecast error not included, load following process not included (only regulation process exists for system balancing need).

Two sets of plots were generated to show the study results.

In plot set 1, the results are presented in a form that comparison between the hour by hour ancillary service requirements with wind and without wind can be easily made. Each figure compares the maximum capacity (MW) or ramp rate (MW/min) requirement between 2006 and a future year. The requirement is shown hour by hour for 24 hours of a day. The green bars in a figure are data for 2006, and red lines correspond to a future year 20xx. The tip point of the green bars and the red arrows correspond to "with wind" conditions, while the flat end of the green bars or the red lines correspond to "without wind" conditions. The length of the bars and the lines indicate the contribution of wind generation to the capacity or ramping requirements for the year 2006 or a future year 20xx correspondingly. By comparing the tip points of the bars and the lines, one can see the expected increment of the capacity and ramping requirement for the corresponding hours. It is important to understand that both the tips and the flats correspond to the maximum capacity and ramping requirements for the corresponding hours of the year (with certain specified percentage of extreme cases excluded from consideration, e.g., 5% for load following and 2.5% for regulation).

Figure 8 and Figure 9 show the load-following capacity and ramp rate requirements in October, respectively. The increased capacity and ramp rate requirements with 6300 MW of wind integrated into the BPA system in 2010 are obviously seen. The amount of real-time dispatch capacity reserve on both sides (up and down) can be determined accordingly. The results shown here include the effect of load and wind forecast errors. The values will be smaller when forecast errors are not considered.

Plots in set 2 show the capacity and ramp requirement for load following and regulation for all months in the years 2006 through 2010, with and without wind. The horizontal axis in the figures is the installed wind capacity corresponding to year 2006 through 2010. A specified percentage of extreme cases were excluded from consideration, e.g., 5% for the load following and 2.5% for regulation. Figure 10 and Figure 11 show the requirements for the load-following process, which are examples of plots in set 2. Again, the results shown include the effect of load and wind forecast errors.

Please see Appendix IV for more results for case 1) (with forecast errors) and Appendix V for case 2) (not considering forecast errors). Results for case 3) and 4) are not included due to the length of the document, but they are available upon request.

Figure 8. Load-following capacity requirements in October

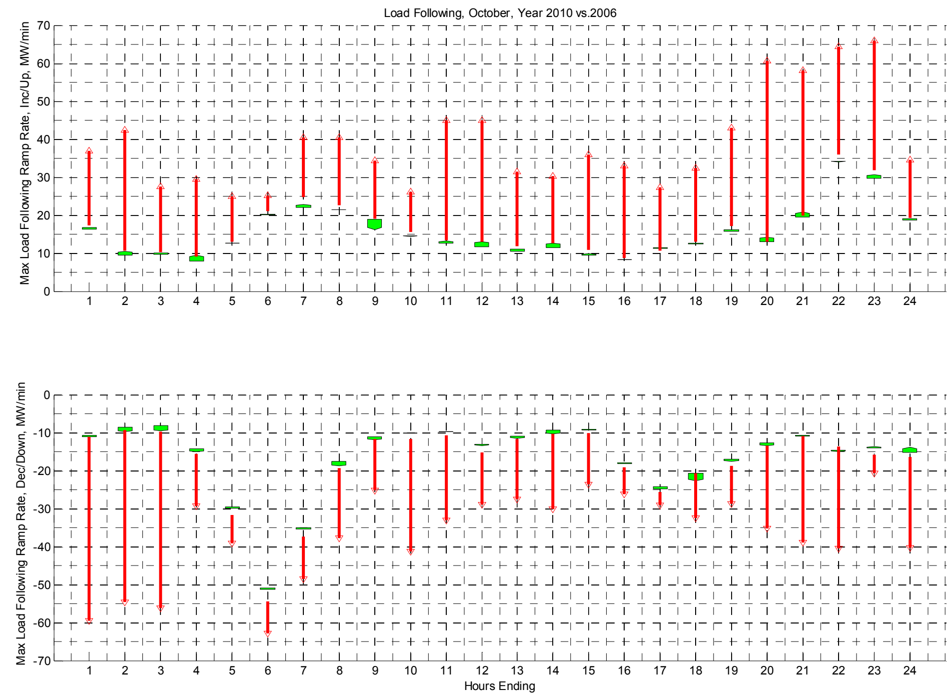

Figure 9. Load-following ramp rate requirements in October

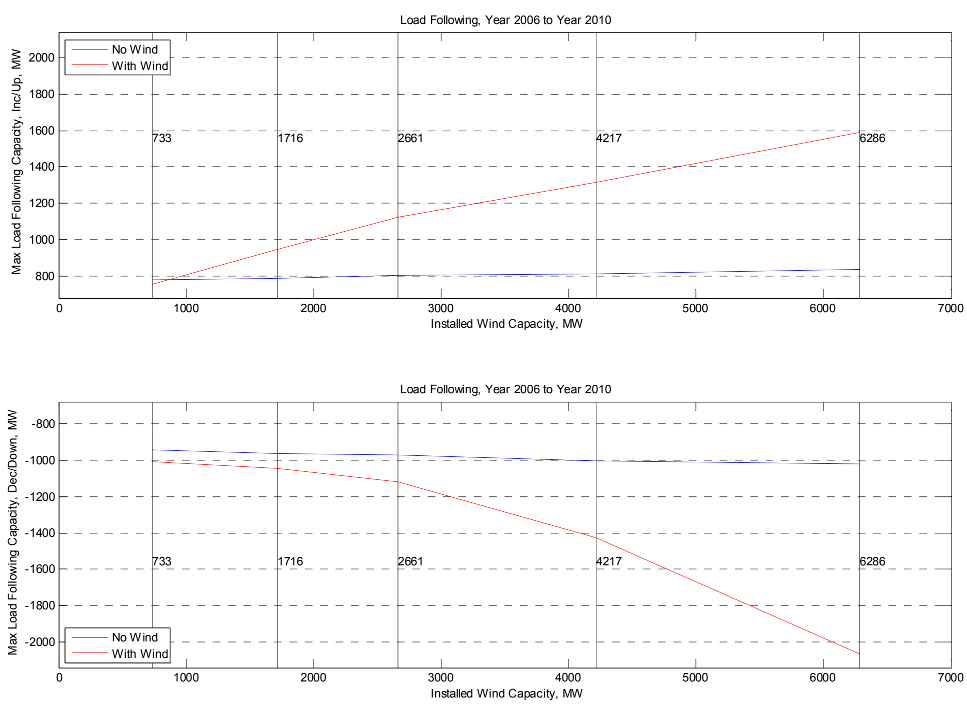

Figure 10. Load-following capacity requirement for year 2006 through 2010

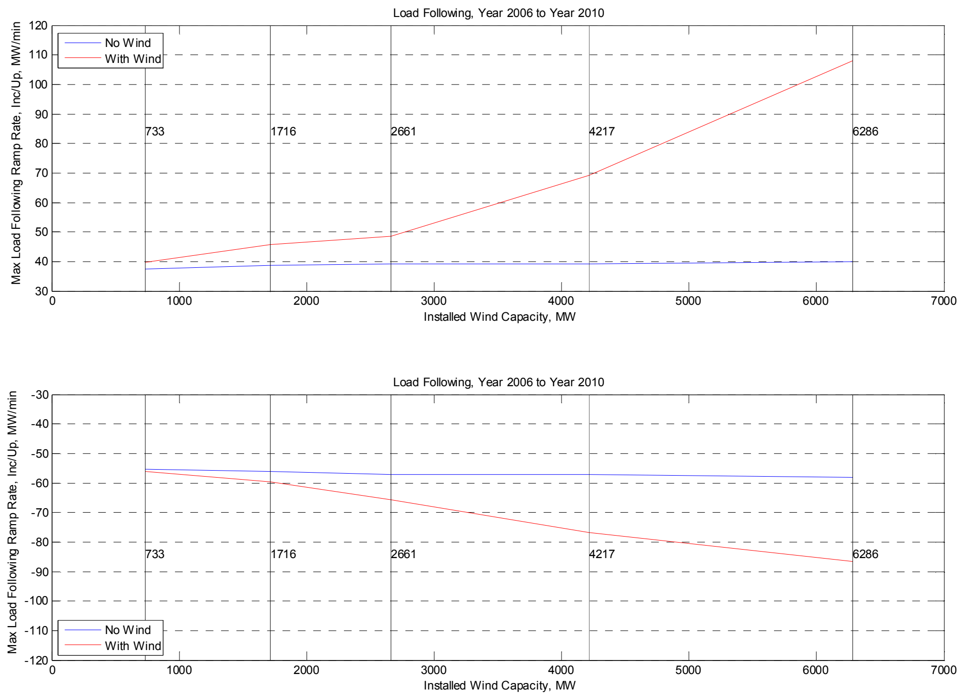

Figure 11 Load-following ramp rate requirement for year 2006 through 2010

6.0 CONCLUSIONS AND RECOMMENDATIONS FOR IMPROVEMENTS

A methodology is developed to study the impact of wind on BPA power system load following and regulation processes. It mimics the balancing processes in the power system using statistical simulations. Generator capacity, ramp rate and ramp duration requirements can all be assessed with the characteristics extracted from load following and regulation data using the proposed methodology. The experience of applying this methodology to the BPA power system proves its effectiveness.

The main findings resulting from the study of BPA system data for different cases include the following (the requirements mentioned below include both capacity and ramp requirements):

- The reserve requirements for regulation process when no load following process exists are approximately the sum of load following and regulation requirements when there is a load following process.
- Shorter load following interval (10 minutes) results in smaller regulation requirements than a longer load following interval (15 minutes), while the load following requirements in both cases are approximately the same.
- Forecast errors on wind and load increase the load following and regulation requirements, sometimes dramatically (1500 MW difference has been seen in the 2010 case. However, this type of events is infrequent and therefore is removed as outliers and not shown in the result figures).
- Load following requirements increased by wind are much more than the increase on regulation requirements: in case 3), for assumed wind power capacity of 6300 MW in 2010, the maximum increase for load following capacity is 400 MW Up and 500 MW Down vs. 90 MW Up and 60 MW Down for regulation capacity.
- The distribution of load following and regulation requirements is not normal. It has long tails along the capacity or ramp axis, which means there are infrequent occasions that the system needs very high capacity and ramp capability for balancing processes. The tail events are usually the results of high wind and load ramps superposed on forecast errors.

Results of the study have been disseminated worldwide. Papers have been presented at the IEEE Transmission and Distribution Conference (Chicago, IL, 2008), 7th Large Scale Wind Integration Workshop in Madrid, Spain (2008), European Energy Market Conference in Lisbon, Portugal (2008), and Windpower 2008 Conference and Exhibition (Houston, TX). The methodology was also used in a recent study conducted by PNNL for the California Independent System Operator (California ISO).

We recommend the following actions for BPA to effectively manage the operational impacts of wind:

- Evaluate the need in both capacity and ramp capability for load following and regulation services at projected wind penetration levels in future years.

- Evaluate the capacity and ramp capability of BPA's existing generation resources that can be used in the load following and regulation processes. Ensure the adequacy of system balancing resources.

- Develop a market mechanism to encourage more generating resources or other flexible resources such as energy storage and demand response to participate in the balancing processes. This will help reducing the balancing obligations on the already very constrained BPA hydro system and potentially lower the balancing cost.

- Incorporate wind forecast into day ahead scheduling and real-time scheduling processes to reduce the need for reserves.

- Develop a mechanism to encourage wind power plants to stay with their schedules (based on forecasts).

- Analyzing the frequency, severity and consequences of tail events in the BPA system and build strategies to deal with tail events.

We recommend doing the following in Phase II to improve the methodology and the accuracy and robustness of the study results:

- Improving the credibility of data sets, especially future wind data.

- Randomization of the study using Monte Carlo simulation approach, which includes:
    - The use of 3 years of the actual load data to capture the variability characteristics;

    - Use randomly generated wind generation forecast errors to produce wind generation schedules (based on certain probability distribution characteristic and autocorrelation between the subsequent forecasts; this information can be calculated based on the 3Tier historical data);

    - Similarly, use randomly generated load-forecast errors to produce load schedules. Note that in Phase I study we just used scaled-up 2006 load schedules.

- Discuss with other industry experts to validate the methodology.

- Investigate and summarize the world experience on analyzing and mitigating the operational impacts of wind integration.

7.0 REFERENCES

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APPENDIX I

Summary of Data Preparation and Simulation Procedures

APPENDIX I: SUMMARY OF DATA PREPARATION AND SIMULATION PROCEDURES

1. Actual load (L_a) and actual wind (W_a)

Spec: raw data for 4 months of a year, 1 min interval. 1.5% yearly increase for load in future years. Actual wind generation is provided for every year.

Source: BPA

2. Load forecast

(1) Hour-ahead load forecast (LF_ha):

Spec: data for 4 months of a year, 1 hour interval, use 1.5% yearly increase for future years.

Source: BPA

*20 min ramp is added by PNNL.

(2) Real-time load forecast (LF_rt):

Spec: 10 min interval, 10 min ramp

Source: PNNL

Method: Simulated based on actual load using truncated normal distribution with autocorrelation between two consecutive data points.

Mean = 0, Std = 15 MW, MaxErr = 50 MW, MinErr = -50 MW.

Autocorrelation = 0.6.

The above parameters are based on system size and typical numbers from other utilities.

Parameters are the same for all years.

3. Wind generation forecast

(1) Hour-ahead wind generation forecast (WF_ha):

Spec: 1 hour interval

Source: Generated by PNNL using BPA formula

*20 min ramp is added by PNNL.

(2) Real-time wind generation forecast (WF_rt):

Spec: 10 min interval, 10 min ramp

Source: PNNL

Method: Simulated based on actual wind using naïve persistence model, which assumes the current wind generation is the same as 7.5 min ago.

4. The methodology is based on separation of load following and regulation using the following formulas:

(1) No wind

Load following = LF_rt – LF_ha
Regulation = L_a – LF_rt
L_a: actual load;
LF_ha: hour-ahead load forecast;
LF_rt: real-time load forecast.

(2) With wind
Load following = (LF_rt – LF_ha) – (WF_rt – WF_ha)
Regulation = (L_a – LF_rt) – (W_a – WF_rt)
W_a: actual wind generation;
WF_ ha: hour-ahead wind forecast;
WF_rt: real-time wind forecast.

No dead band is applied on regulation.

5. Process load following and regulation data with swinging door method (a data compression algorithm used in the PI System for data storage) to obtain:
Capacity, Ramp and Ramp Duration.
Deviation in swinging door method is 5 MW.

6. Group data from 5 into each of the 24 hours in a day.

7. Remove 5% extreme cases on capacity, ramp and ramp duration axes (1.67% on each axis) in the load following data and 2.5% in regulation data from step 6.

8. Draw plots based on data from step 7 including:
Plots for capacity and ramp for both load following and regulation.

APPENDIX II.

GENERATING DTA SERIES IN TRUNCATED NORMAL DISTRIBUTION WITH AUTOCORRELATION

APPENDIX II: GENERATING DATA SERIES IN TRUNCATED NORMAL DISTRIBUTION WITH AUTOCORRELATION

A random data series in truncated normal distribution with autocorrelation can be used to represent load or wind forecast errors. An approach to generate such a data series is described as follows.

Assume the length of the (forecast) data series is n. Let a be the determined autocorrelation of the forecast error. We define another coefficient b as:

$$b = \sqrt{1 - a^2} \tag{II.1}$$

Generate a random series X with length n. X is in normal distribution with a specified mean μ and standard deviation σ same as forecast errors, and it lies within the interval E_{max} and E_{min} (maximum and minimum forecast error, respectively), i.e.:

$$X \sim N(\mu, \sigma^2) \text{ and } X \in (E_{\min}, E_{\max}) \tag{II.2}$$

Generate another vacant data series with length n and call it Y. Use x(i) and $y(i)$ to represent the elements of X and Y, respectively. Do the following:

$$y(1) = x(1) \tag{II.3}$$

$$y(i) = a \cdot y(i-1) + b \cdot x(i) \quad i = 2, 3, \cdots, n \tag{II.4}$$

Then Y is a random series with the specified TND and autocorrelation a. The proof is omitted.

APPENDIX III

DISCUSSION ON THE REMOVAL OF EXTREME EVENTS FROM STUDY RESULTS

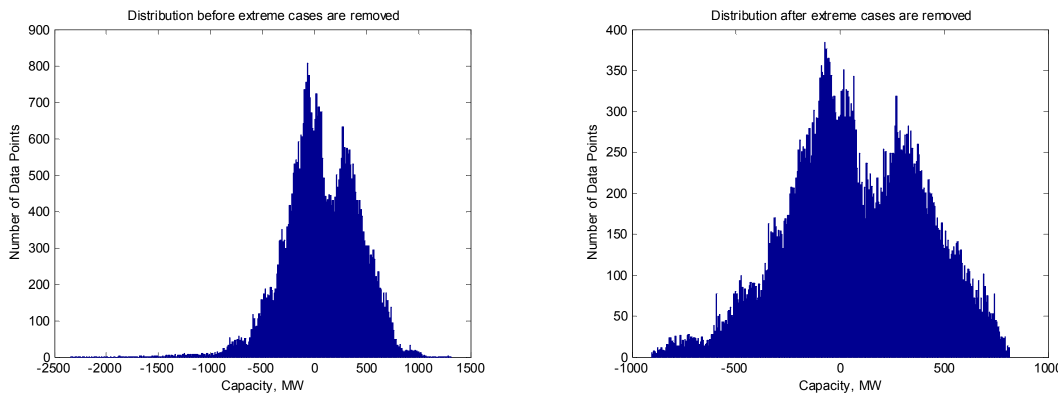
APPENDIX III: DISCUSSION ON THE REMOVAL OF EXTREME EVENTS FROM STUDY RESULTS

There are two options when removing the extreme cases from the load-following and regulation analysis results:

(1) Removing the extreme cases after grouping the swinging door analysis results into the 24 hours of a day. In other words, the percentage of extreme cases is excluded hour by hour.

(2) Removing the extreme cases after processing the entire month's data with swinging door method, and before grouping the results into the 24 hours of a day. This way, the percentage of extreme cases is excluded based on the data of the entire month.
Because the distribution of data are different in each hour, and distribution of hourly data is different from monthly data, the above two options give different results.

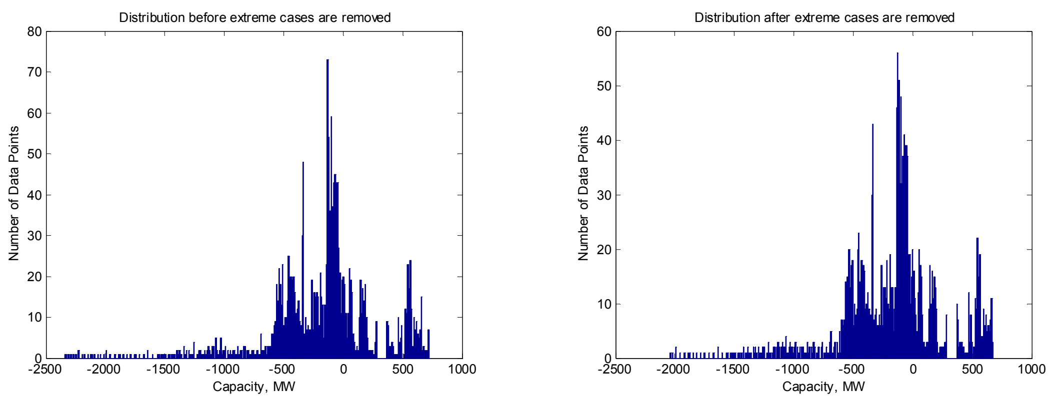
Figure III.1 and Figure III.2 show the distribution of load-following capacity in August 2010 (for all hours), and only in all the hours ending at 18:00 in August 2010, respectively.



(a) **(b)**

Figure III. 1. Distribution of load following capacity in Aug 2010

(1.67% extreme cases are removed on capacity axis in (b))



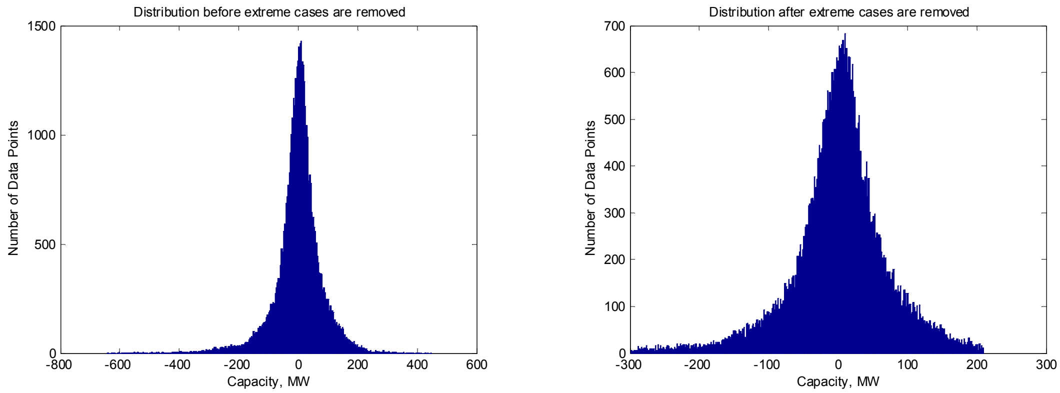
(a) (b)

Figure III. 2. Distribution of load following capacity in hours ending by18:00 in Aug 2010

(1.67% extreme cases are removed on capacity axis in (b))

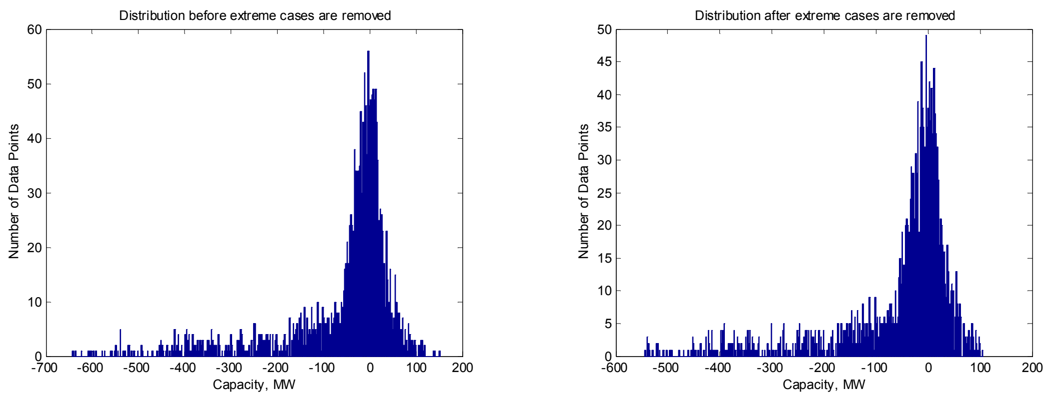
Comparing Figure III.1 and Figure III.2, we can see that after the same percentage of extreme cases is removed, the maximum capacity requirements are quite different. In Figure III.1, which corresponds to option (1), the requirement is about 900 MW; in Figure III.2, which corresponds to option (2), the requirement is about 2000 MW.

Figure III.3 and Figure III.4 show a similar comparison for regulation.



(a) (b)

Figure III. 3 Distribution of regulation capacity in Aug 2010
(1.67% extreme cases are removed on capacity axis in (b))

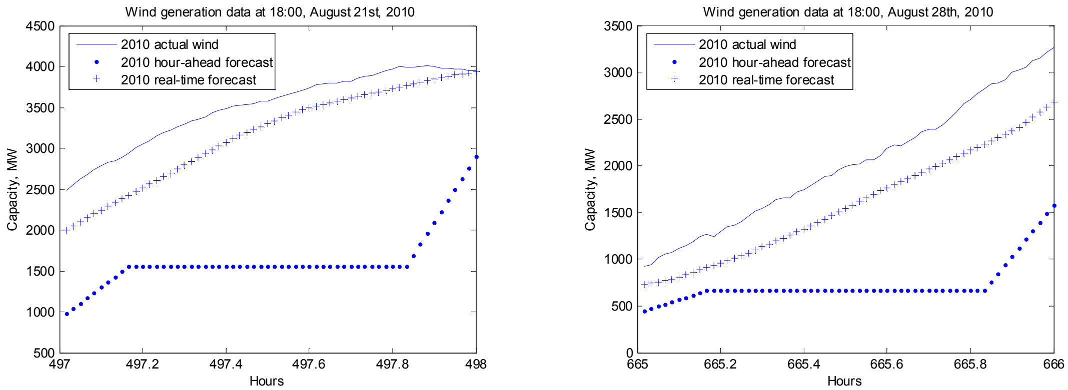


(a) (b)

Figure III. 4. Distribution of regulation capacity in hours ending by 18:00, Aug 2010
(1.67% extreme cases are removed on capacity axis in (b))

Comparing Figure III.3 and Figure III.4, we can see that after the same percentage of extreme cases is removed, the requirement in Figure III.3 is about 300 MW and the requirement in Figure III.4 is about 550 MW.

Figure III.5 shows the actual and forecast wind curve in hours ending by 18:00 on August 21 and 28 in 2010 to verify the need for large regulation and load-following capacity seen in Fig. a.1 through Figure III.4.



(a) (b)

Figure III. 5 Wind data at 18:00 on Aug 21 and 28, 2010

It can be seen in Figure III.5 that because the ramp rate of actual wind is high (~80 MW/min), the persistence model used for real-time forecast generates an error of abut 80 MW/min * 7.5 min = 600 MW, which must be met using regulation capacity. The hour-ahead forecast error is sometimes larger than 2000 MW, which must be met using load following capacity.

Discussion:

If we choose option (2) to determine capacity requirement, as shown in Figure III.1 and Figure III.3, in the situations shown in Figure III.5 the system will be short of load-following and regulation capacity. Either very large positive or negative ACE will occur for continuous periods within certain operating hours (exceeding 2000 MW for 2010!), or additional units will manually be committed and dispatched and/or system operating reserve will be activated (which will certainly happen in reality). On the other hand, theoretically, because the CPS2 compliance criterion is calculated based on the statistics of an entire month, this may not incur a monthly CPS2 violation. If we choose option (1), we'll have larger capacity requirements, which may only be need for a limited number of cases (that are nevertheless still within the 95% of the cases).

APPENDIX IV

BPA WIND IMPACT STUDY RESULTS CONSIDERING FORECAST ERRORS

APPENDIX IV: BPA WIND IMPACT STUDY RESULTS CONSIDERING FORECAST ERRORS

Plot set 1:
All plots are using 5% for load following, 5% for regulation, and 5 MW swinging door deviation.

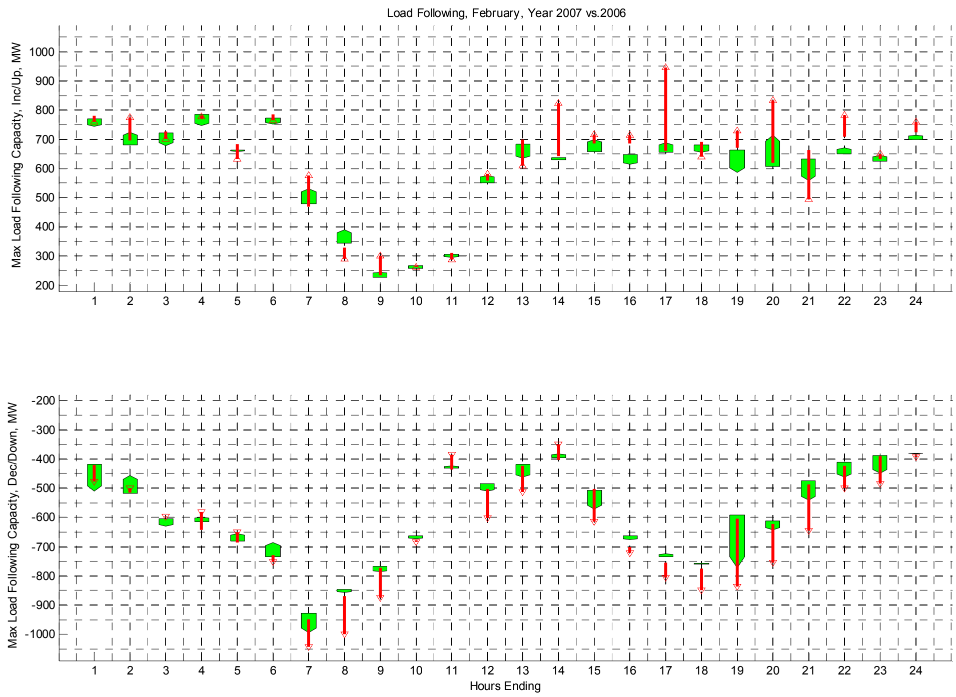


Figure IV. 1 Load following capacity requirement in February, year 2007 vs. 2006

Figure IV. 2 Load following ramp requirement in February, year 2007 vs. 2006

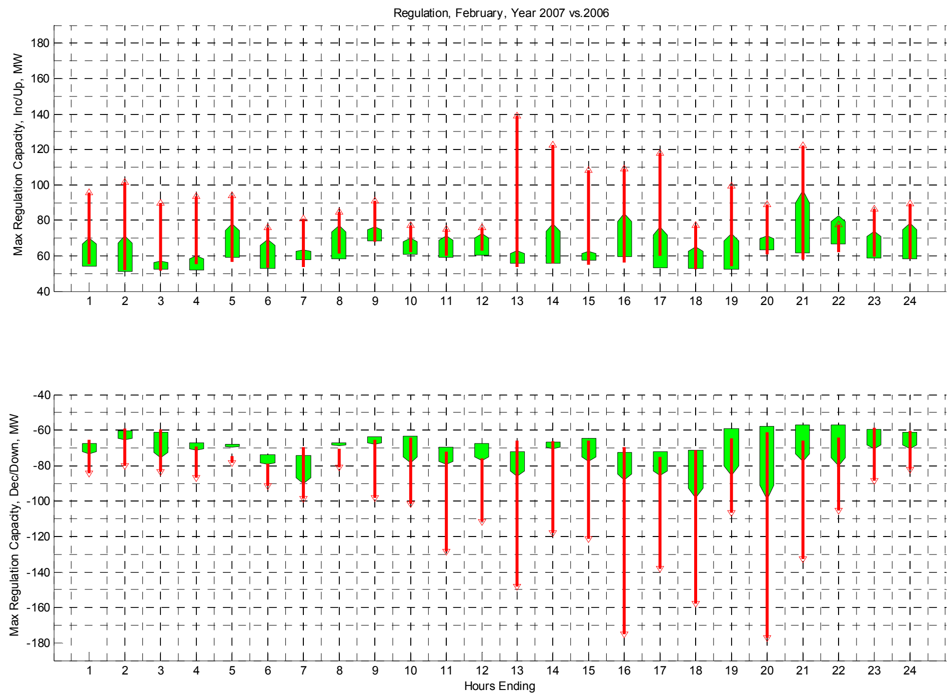


Figure IV. 3 Regulation capacity requirement in February, year 2007 vs. 2006

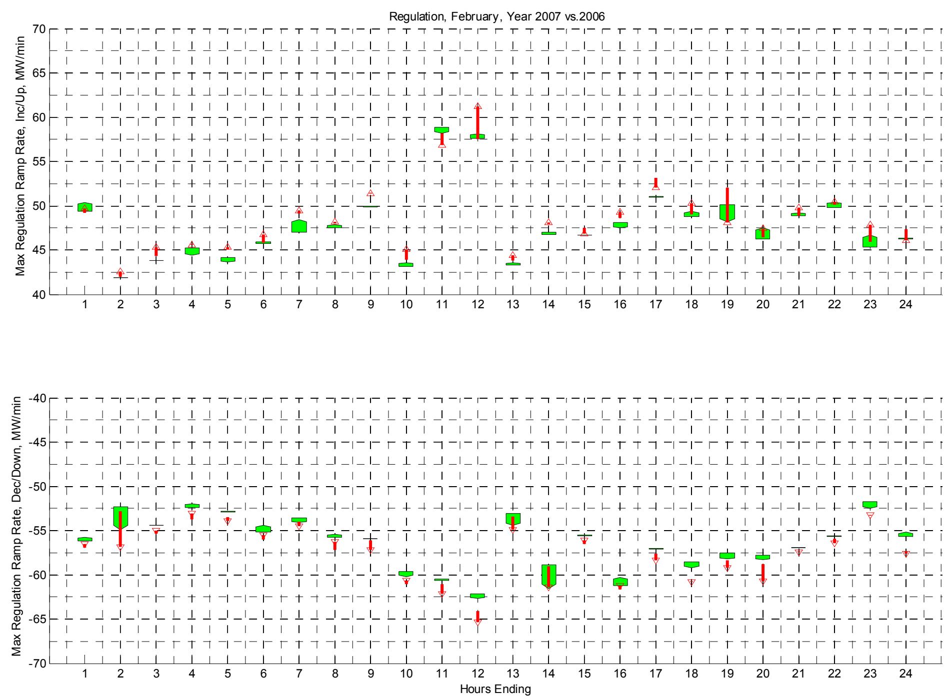


Figure IV. 4 Regulation ramp requirement in February, year 2007 vs. 2006

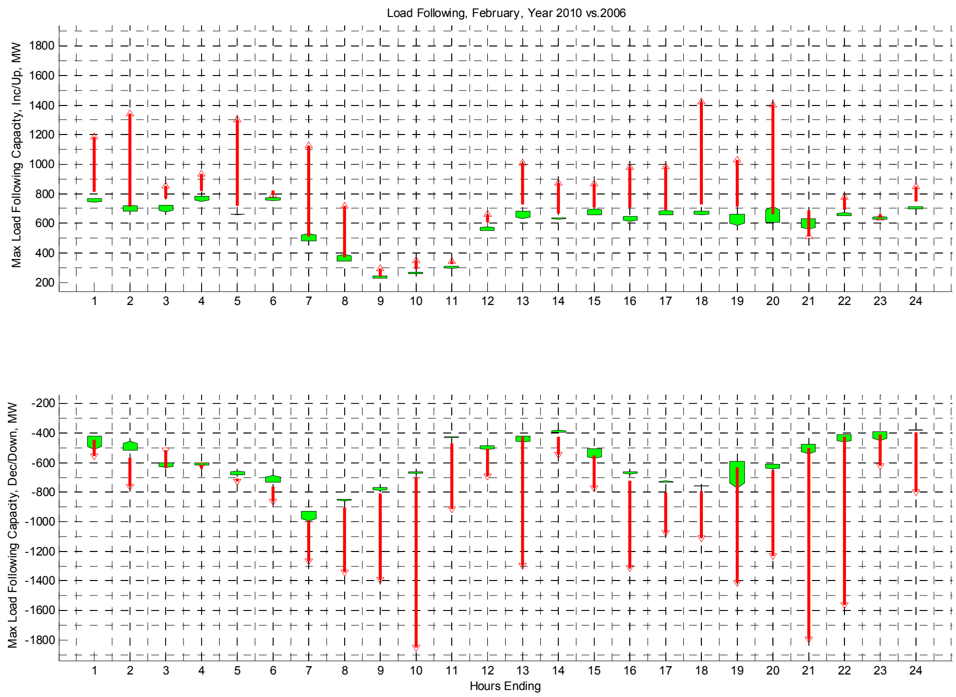


Figure IV. 5 Load following capacity requirement in February, year 2010 vs. 2006

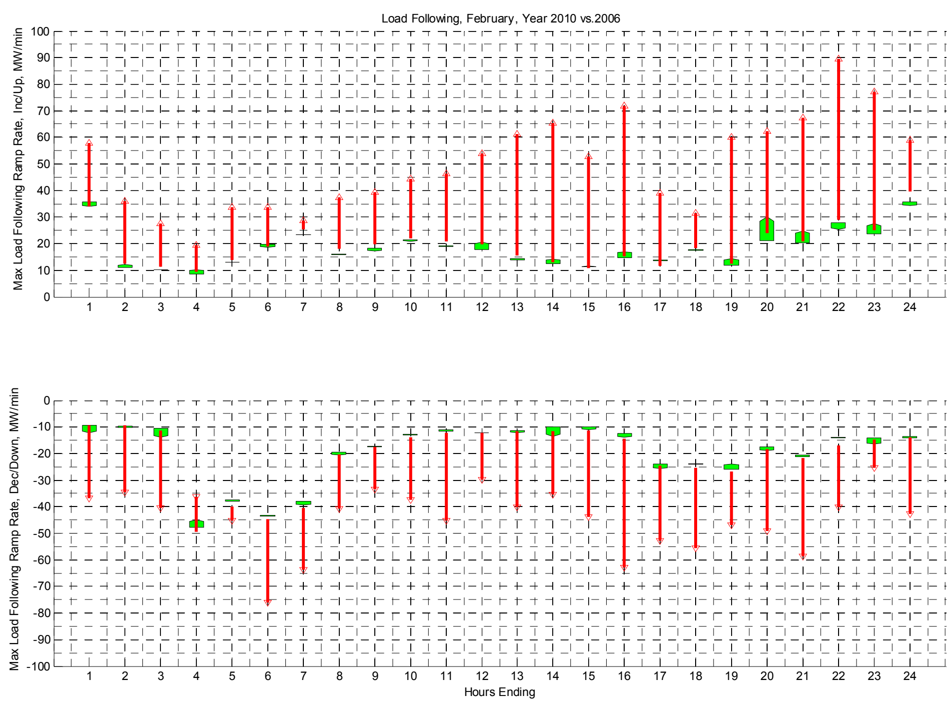


Figure IV. 6 Load following ramp requirement in February, year 2010 vs. 2006

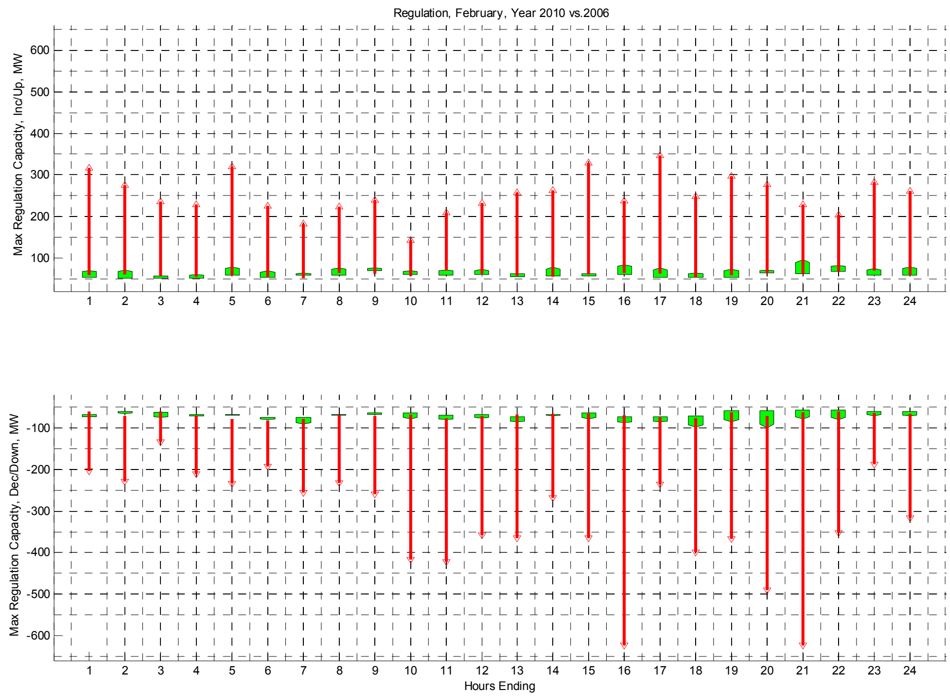


Figure IV. 7 Regulation capacity requirement in February, year 2010 vs. 2006

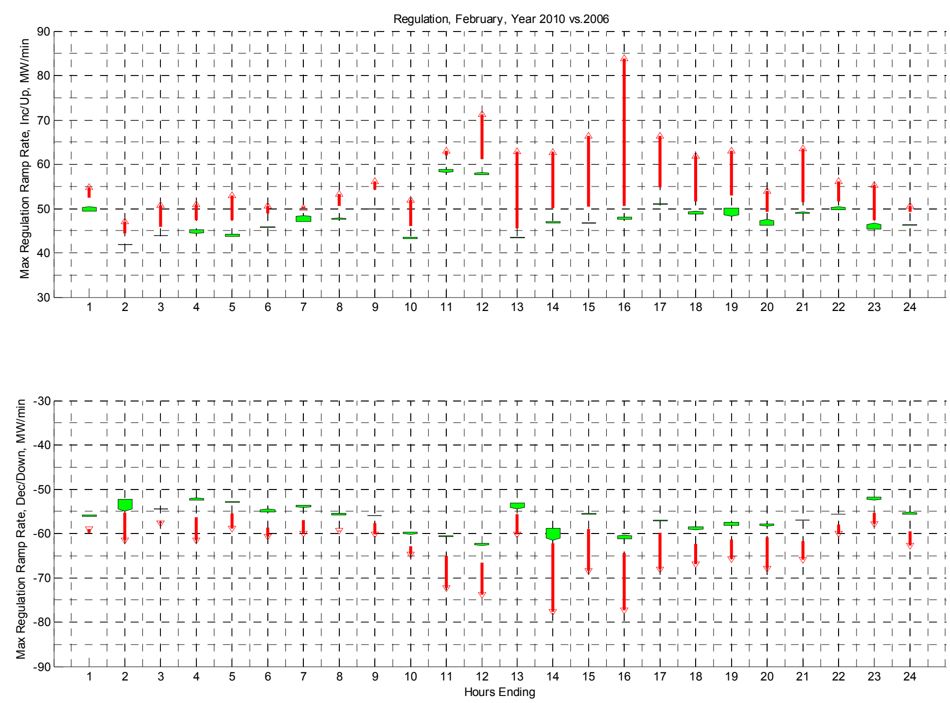


Figure IV. 8 Regulation ramp requirement in February, year 2010 vs. 2006

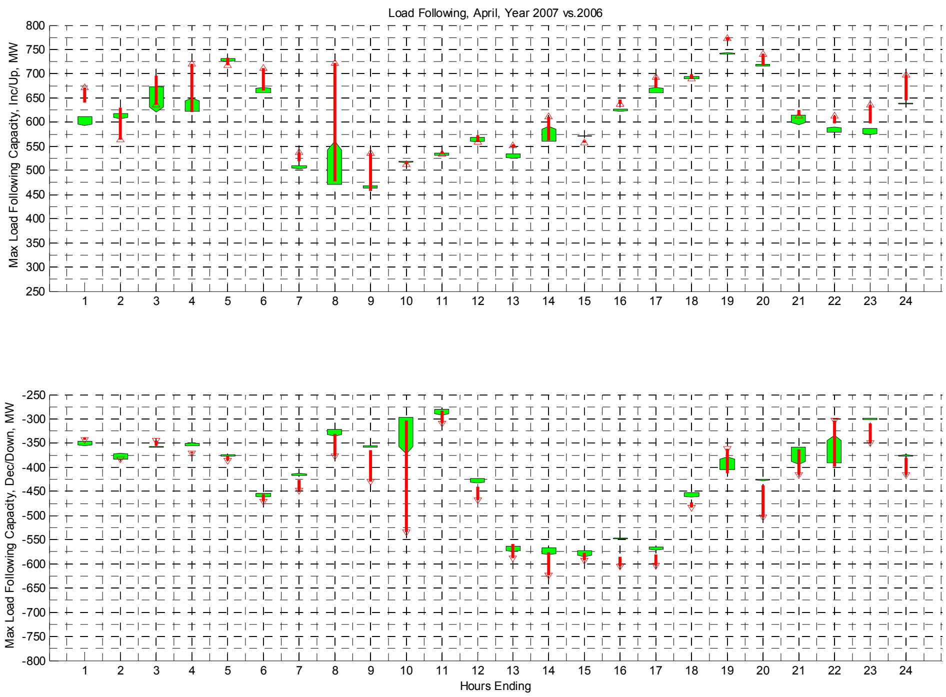


Figure IV. 9 Load following capacity requirement in April, year 2007 vs. 2006

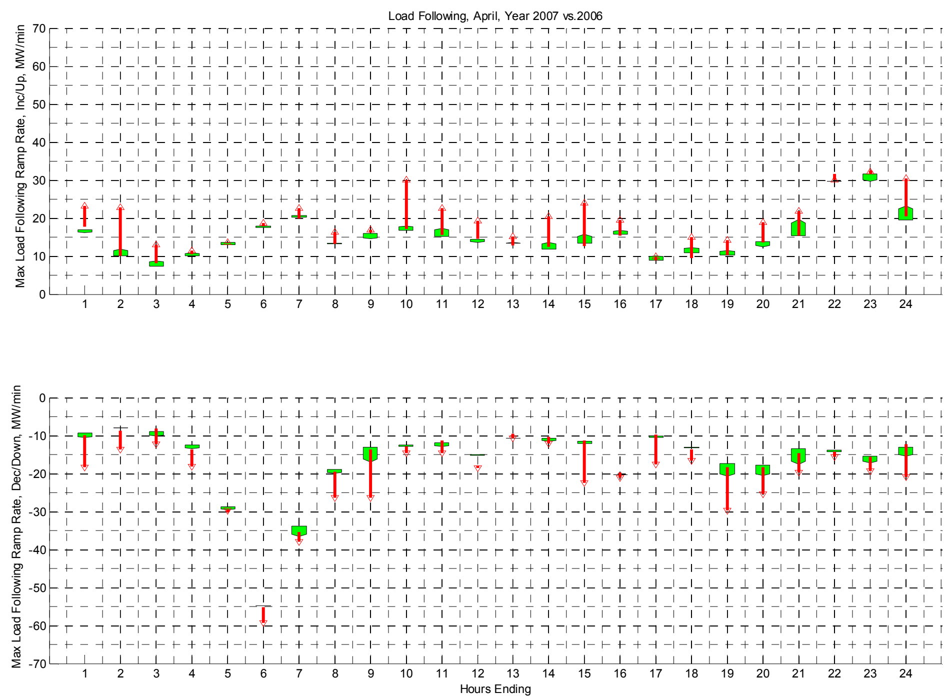


Figure IV. 10 Load following ramp requirement in April, year 2007 vs. 2006

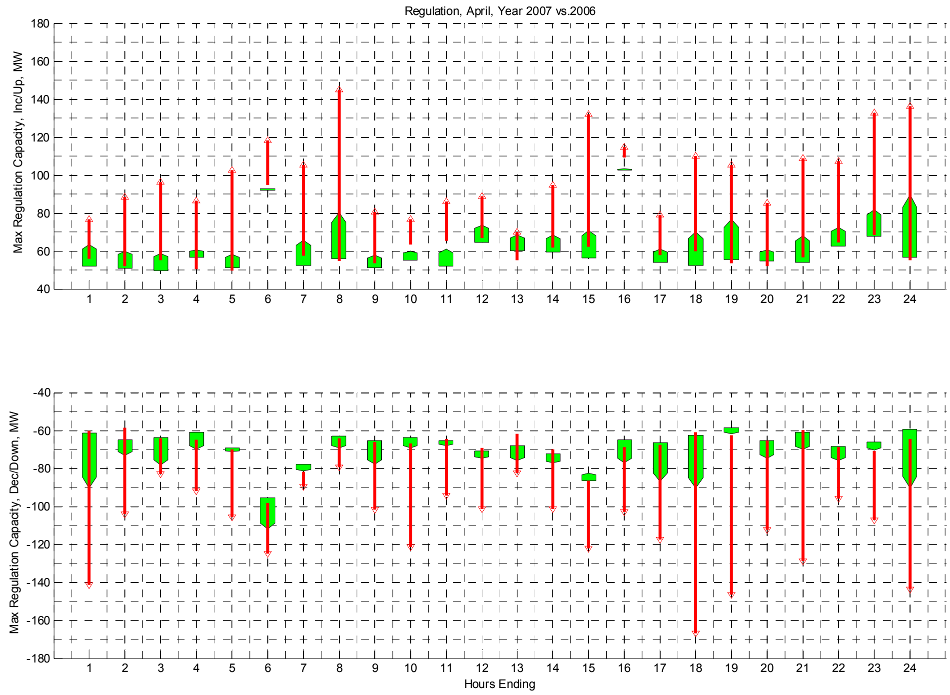


Figure IV. 11 Regulation capacity requirement in April, year 2007 vs. 2006

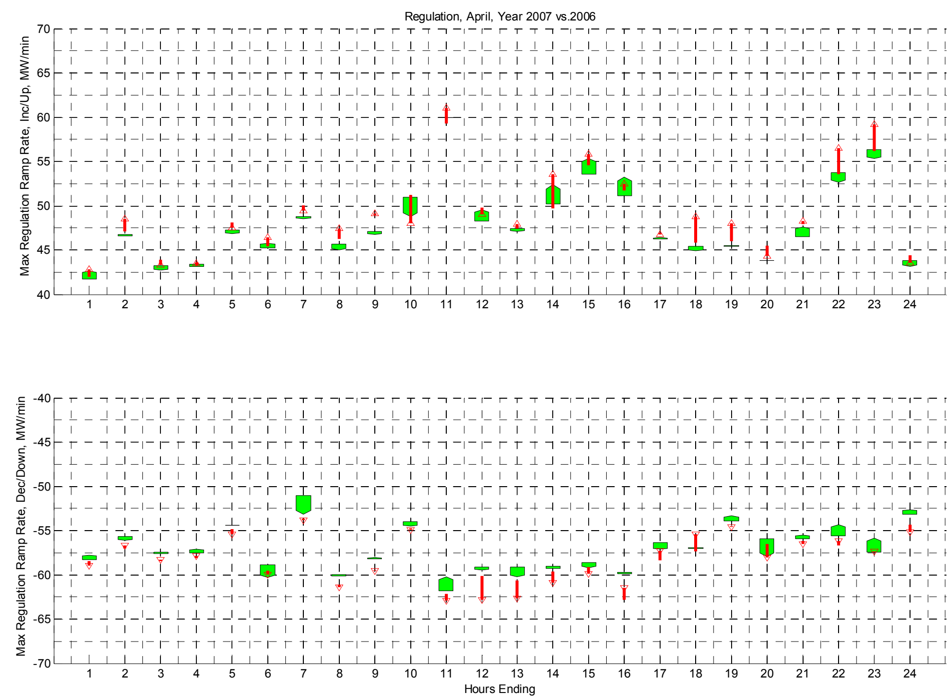


Figure IV. 12 Regulation ramp requirement in April, year 2007 vs. 2006

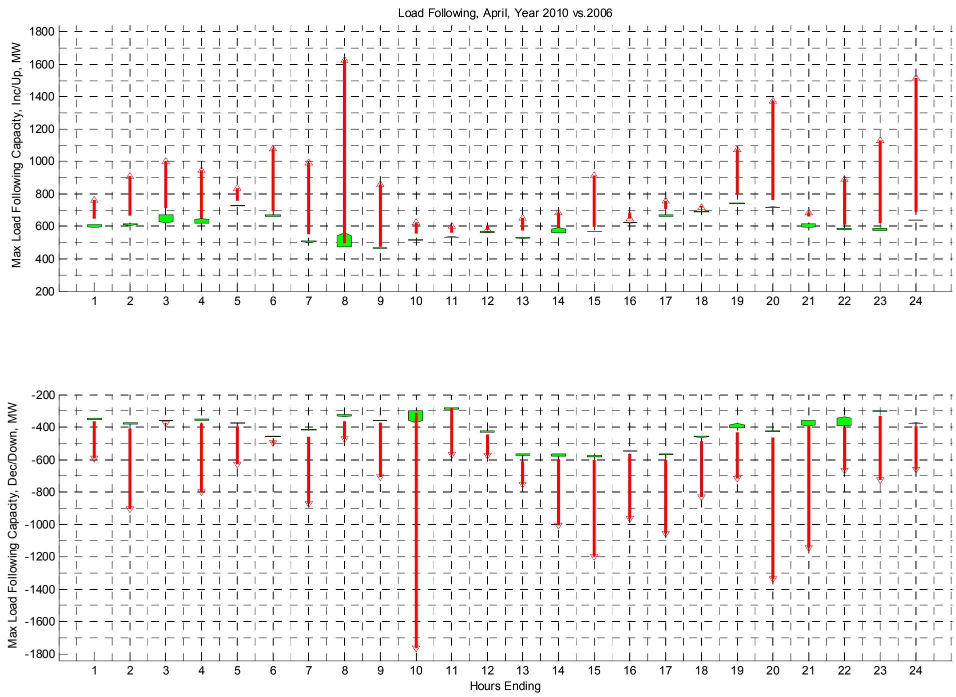


Figure IV. 13 Load following capacity requirement in April, year 2010 vs. 2006

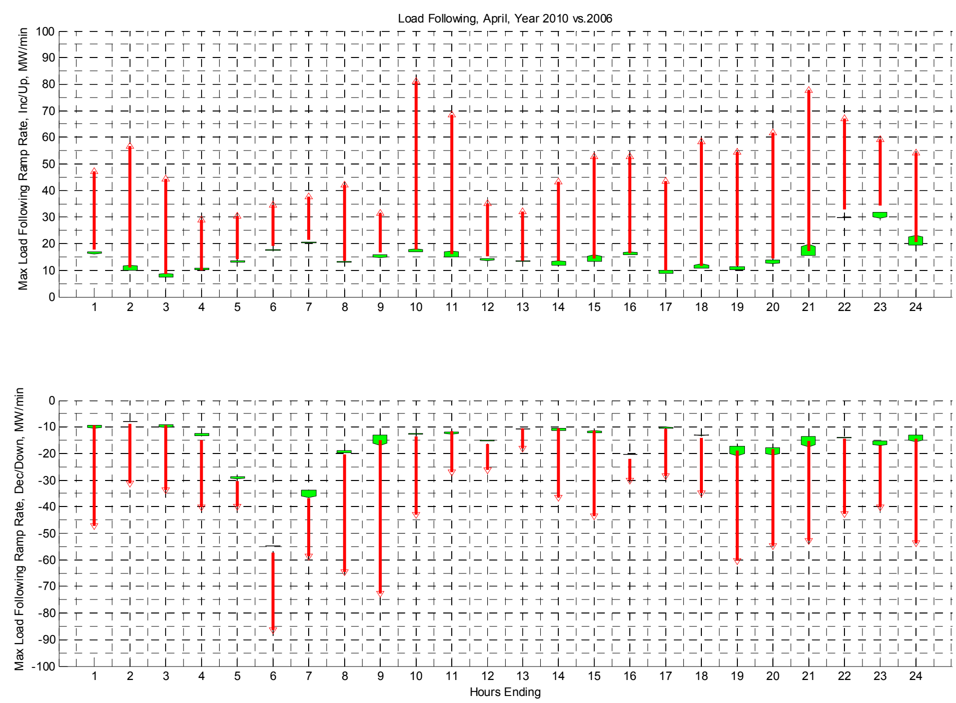


Figure IV. 14 Load following ramp requirement in April, year 2010 vs. 2006

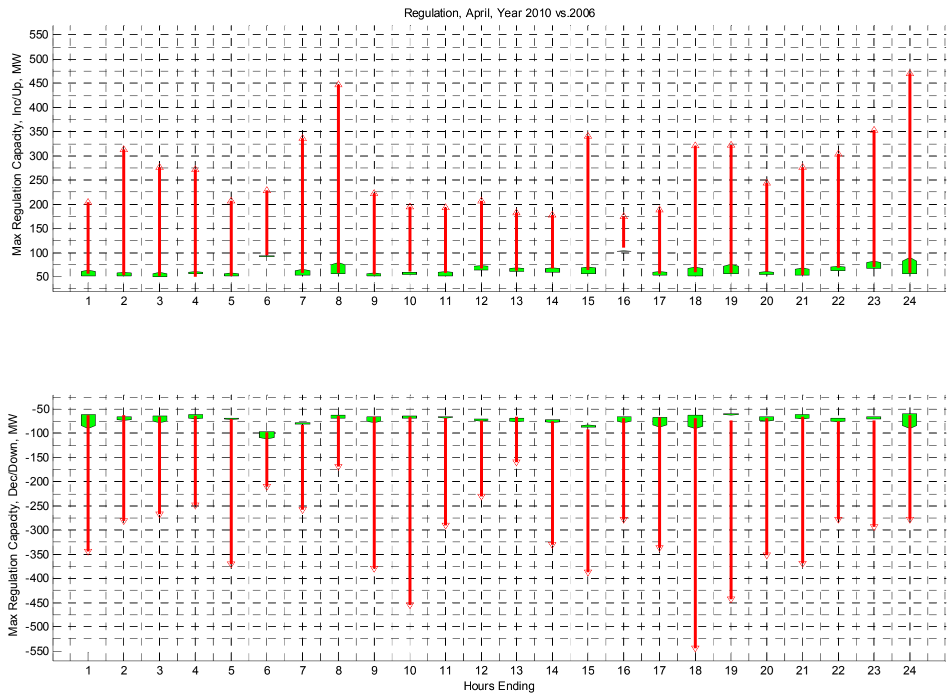


Figure IV. 15 Regulation capacity requirement in April, year 2010 vs. 2006

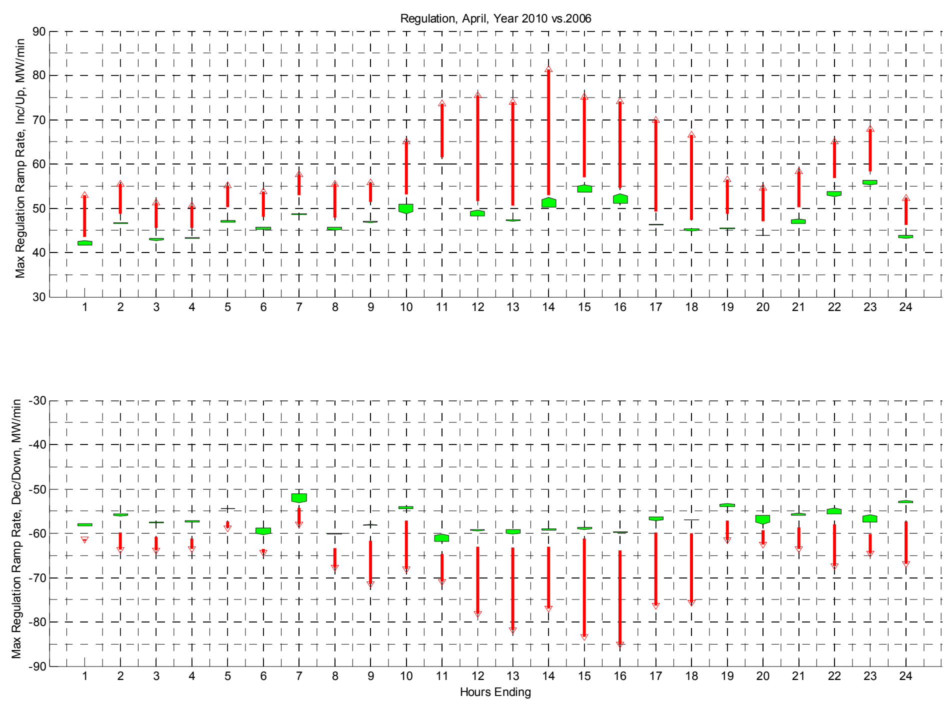


Figure IV. 16 Regulation ramp requirement in April, year 2010 vs. 2006

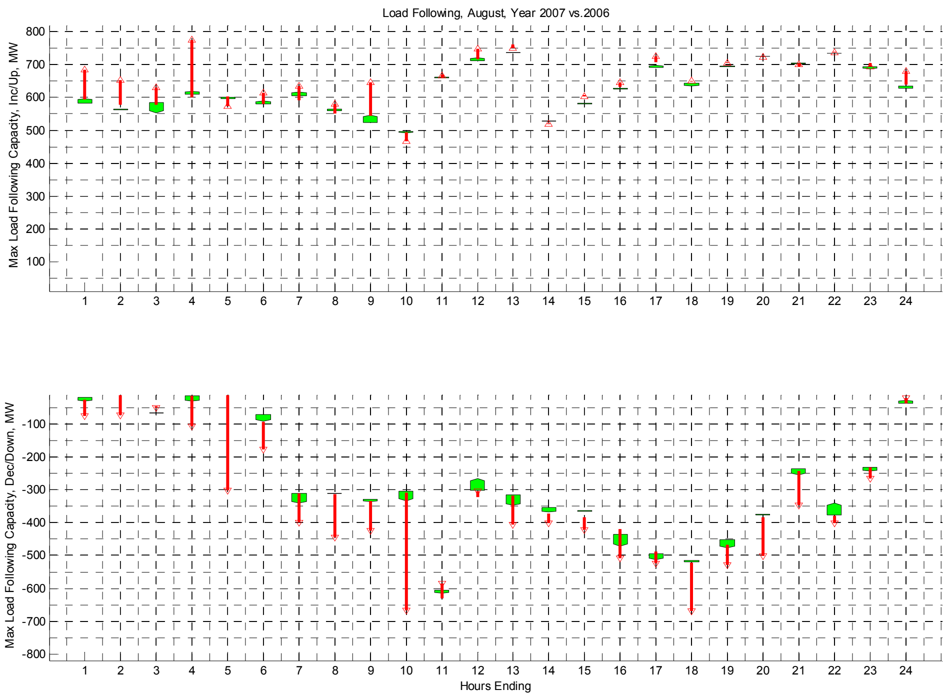


Figure IV. 17 Load following capacity requirement in August, year 2007 vs. 2006

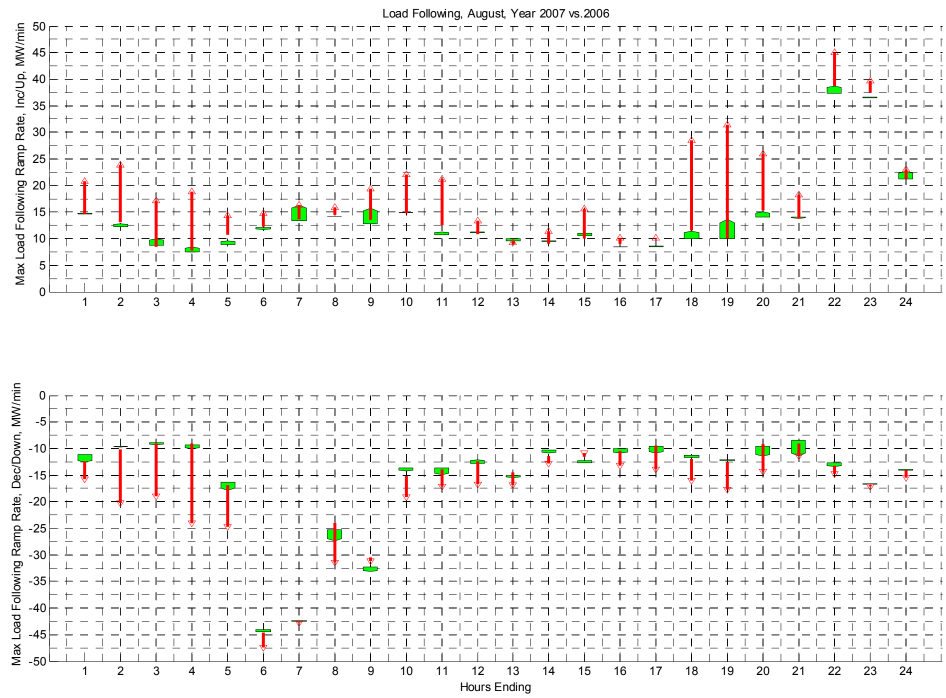


Figure IV. 18 Load following ramp requirement in August, year 2007 vs. 2006

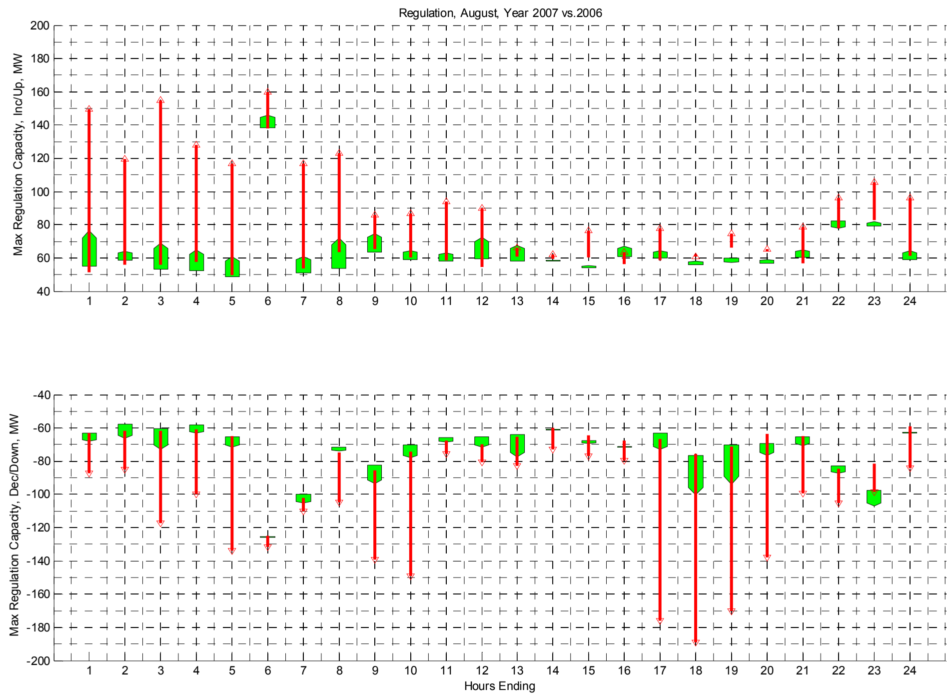


Figure IV. 19 Regulation capacity requirement in August, year 2007 vs. 2006

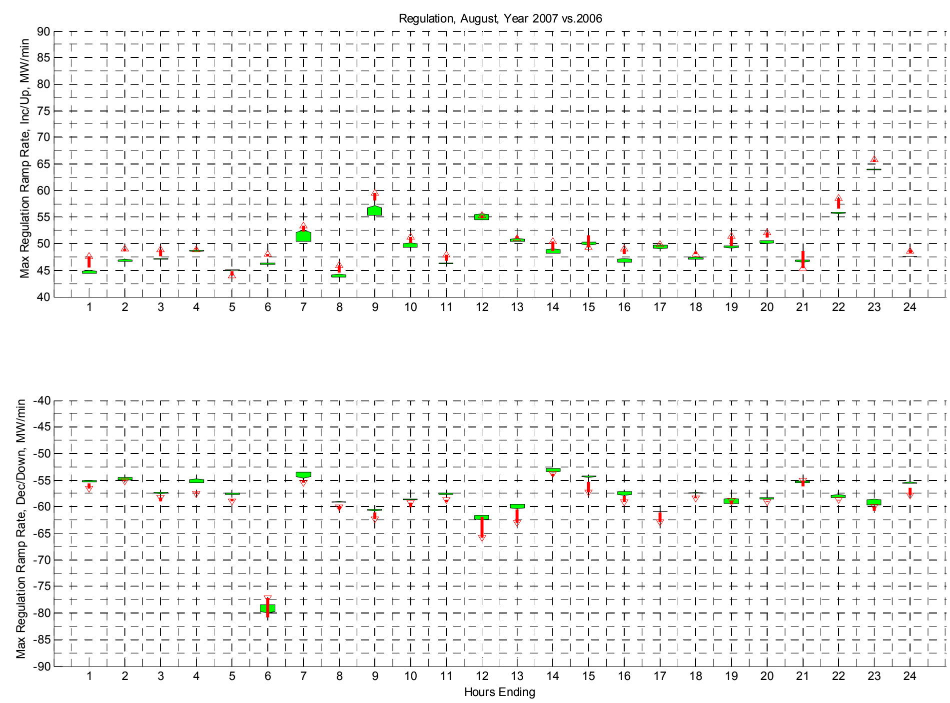


Figure IV. 20 Regulation ramp requirement in August, year 2007 vs. 2006

Figure IV. 21 Load following capacity requirement in August, year 2010 vs. 2006

Figure IV. 22 Load following ramp requirement in August, year 2010 vs. 2006

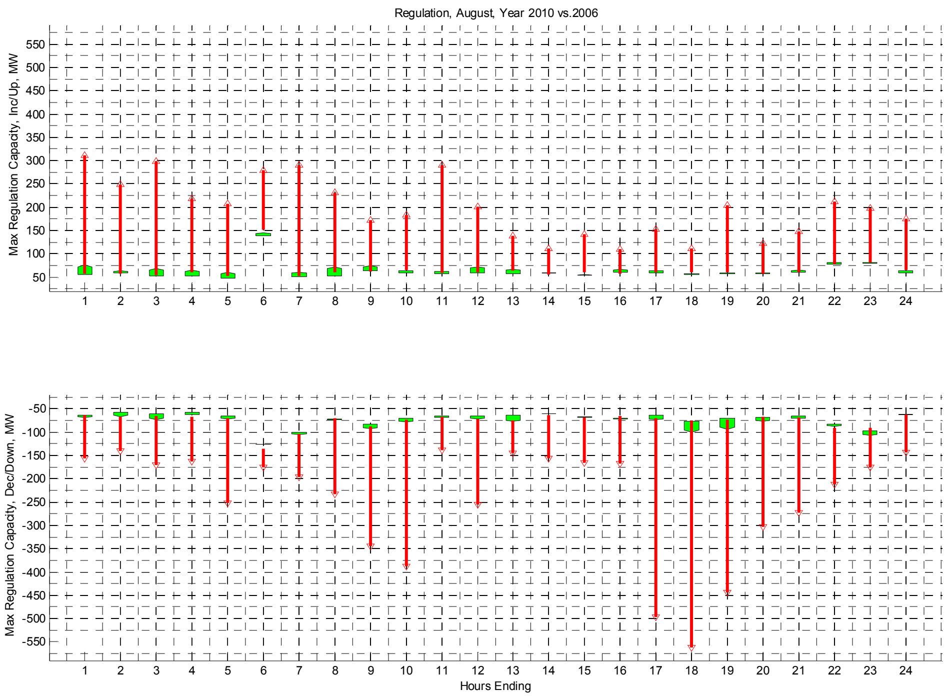


Figure IV. 23 Regulation capacity requirement in August, year 2007 vs. 2006

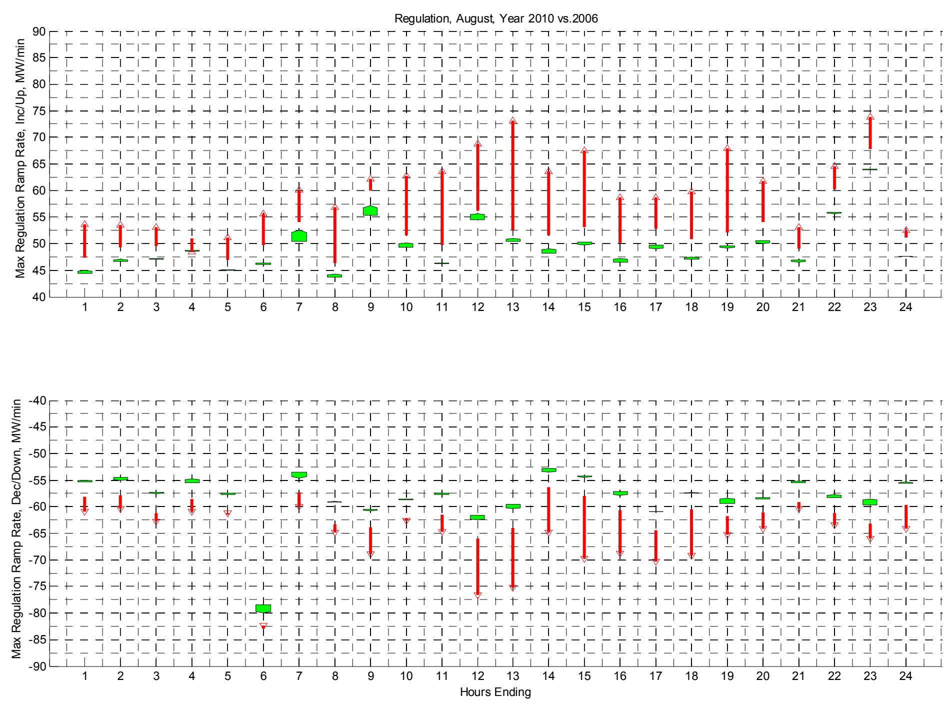


Figure IV. 24 Regulation ramp requirement in August, year 2007 vs. 2006

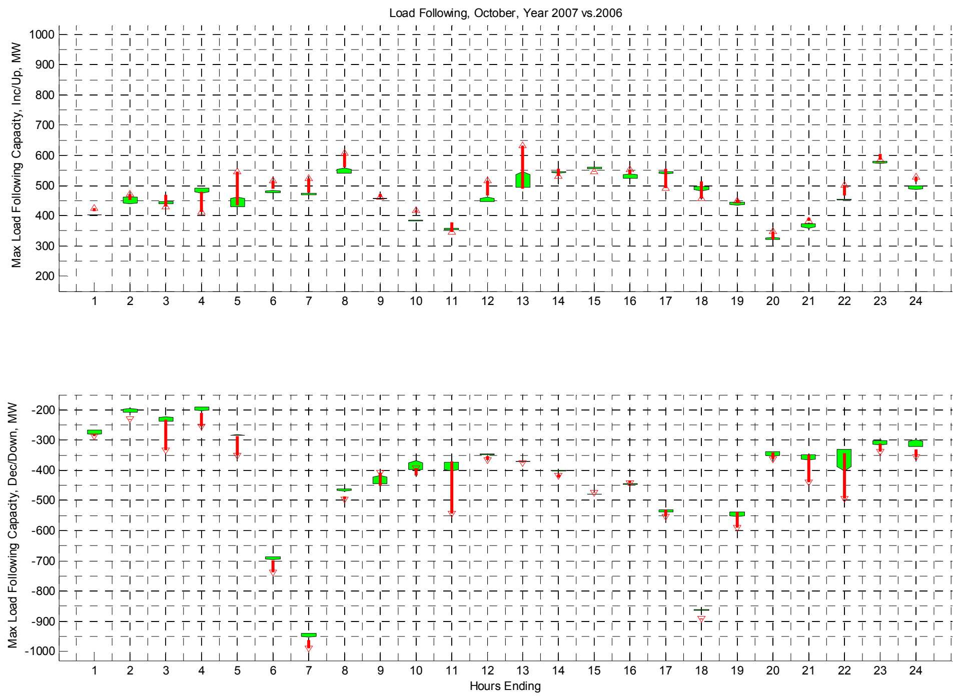


Figure IV. 25 Load following capacity requirement in October, year 2007 vs. 2006

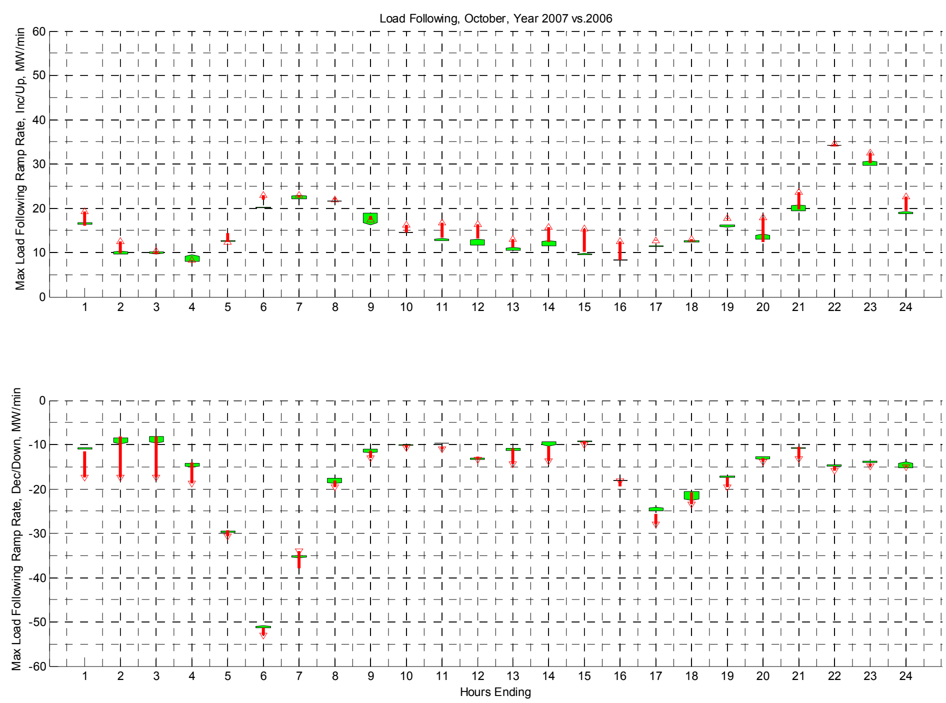


Figure IV. 26 Load following ramp requirement in October, year 2007 vs. 2006

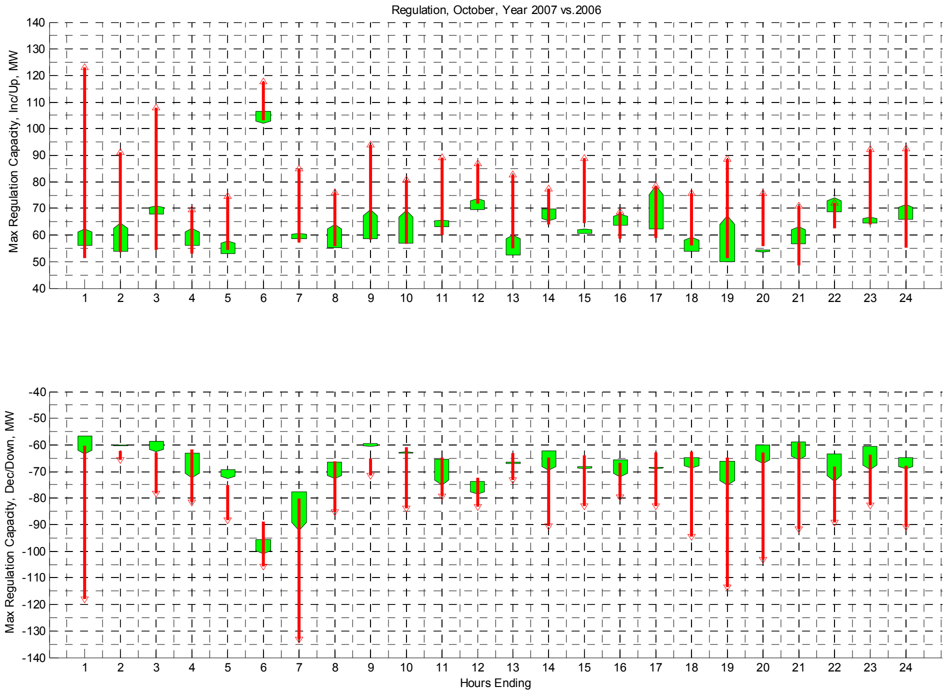


Figure IV. 27 Regulation capacity requirement in October, year 2007 vs. 2006

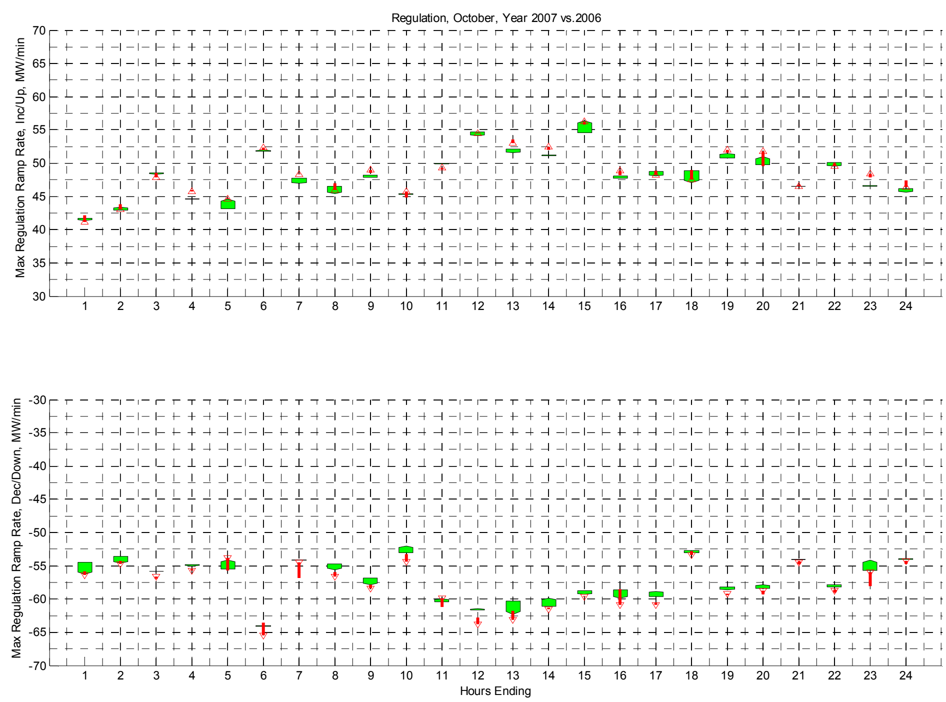


Figure IV. 28 Regulation ramp requirement in October, year 2007 vs. 2006

Figure IV. 29 Load following capacity requirement in October, year 2010 vs. 2006

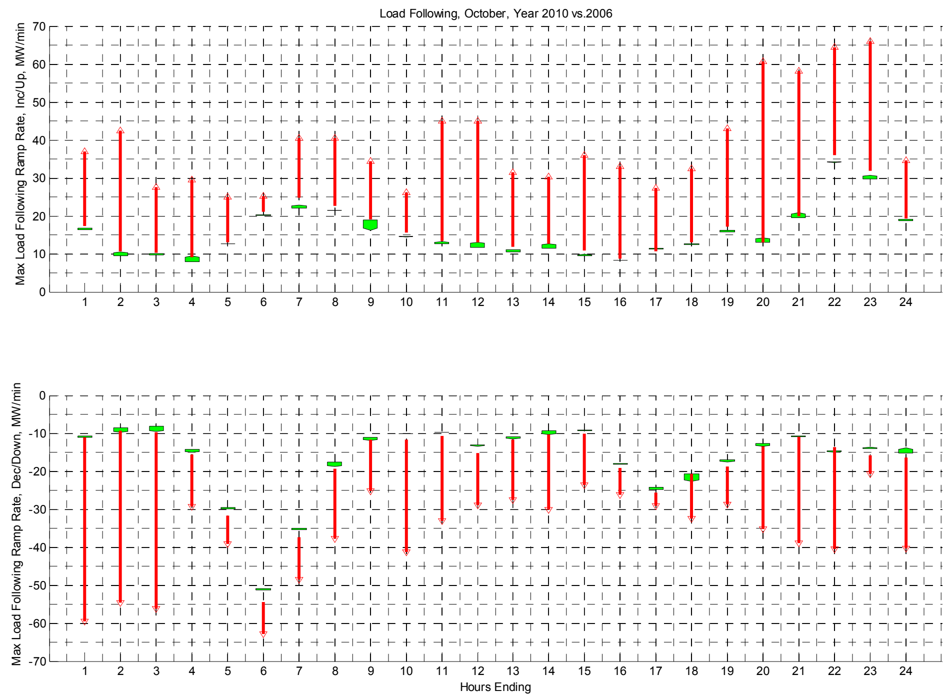


Figure IV. 30 Load following ramp requirement in October, year 2010 vs. 2006

Figure IV. 31 Regulation capacity requirement in October, year 2010 vs. 2006

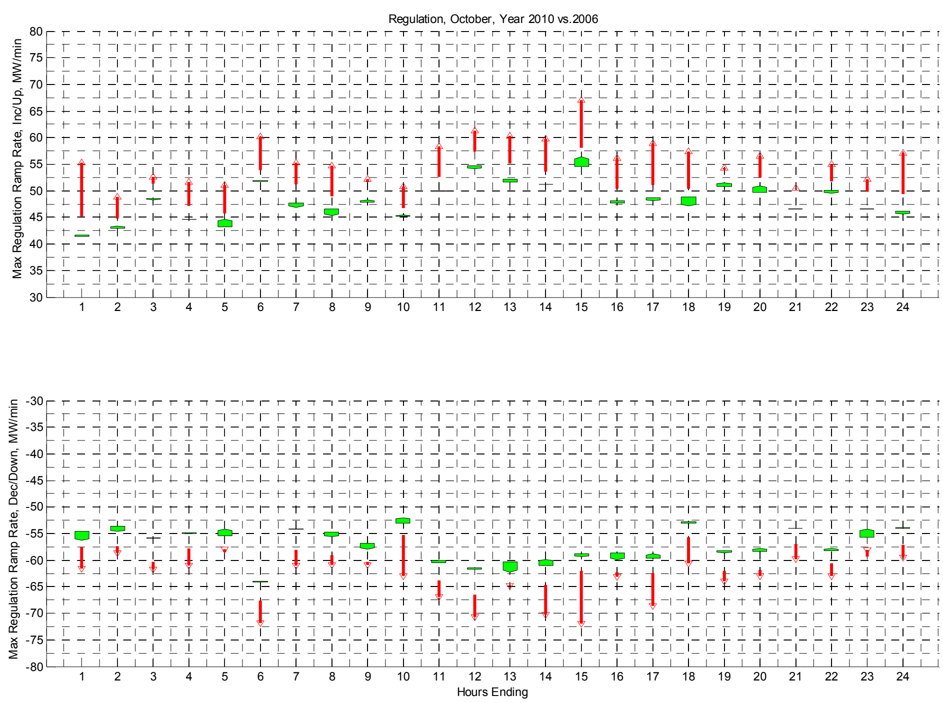


Figure IV. 32 Regulation ramp requirement in October, year 2010 vs. 2006

Plot set 2:

All plots are based on the case with 5% load following, 2.5% regulation, and 5 MW swinging door deviation:

1. Max load following capacity for all months in year 2006 to 2010: with and without wind

2. Max regulation capacity for all months in year 2006 to 2010: with and without wind

3. Max load-following ramp rate for all months in year 2006 to 2010: with and without wind

4. Max regulation ramp rate for all months in year 2006 to 2010: with and without wind

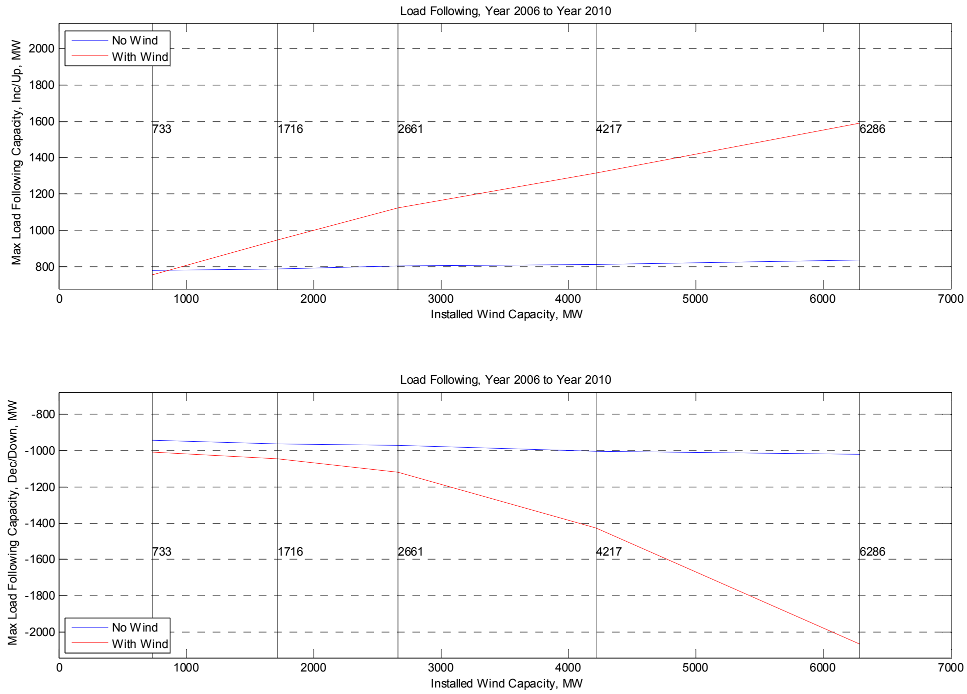


Figure IV. 33 Load following capacity requirement for year 2006 through 2010

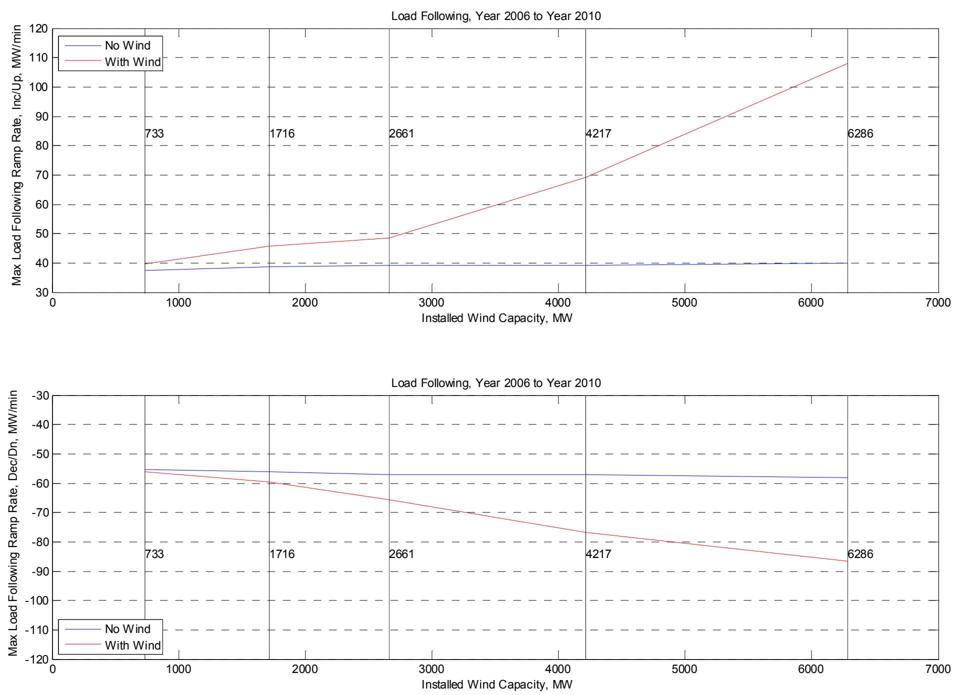


Figure IV. 34 Load following ramp requirement for year 2006 through 2010

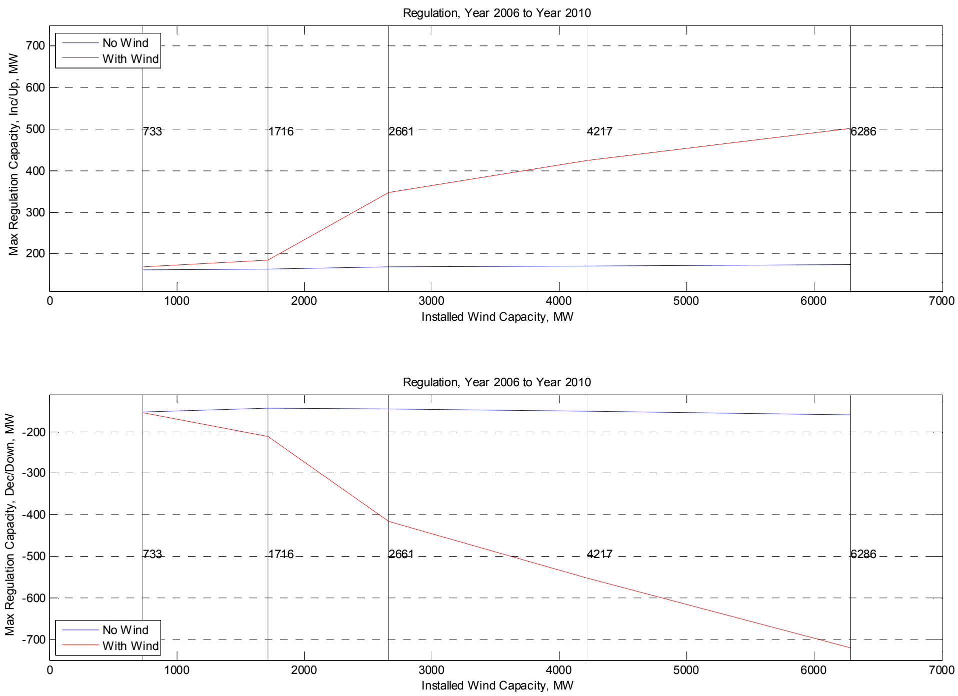


Figure IV. 35 Regulation capacity requirement for year 2006 through 2010

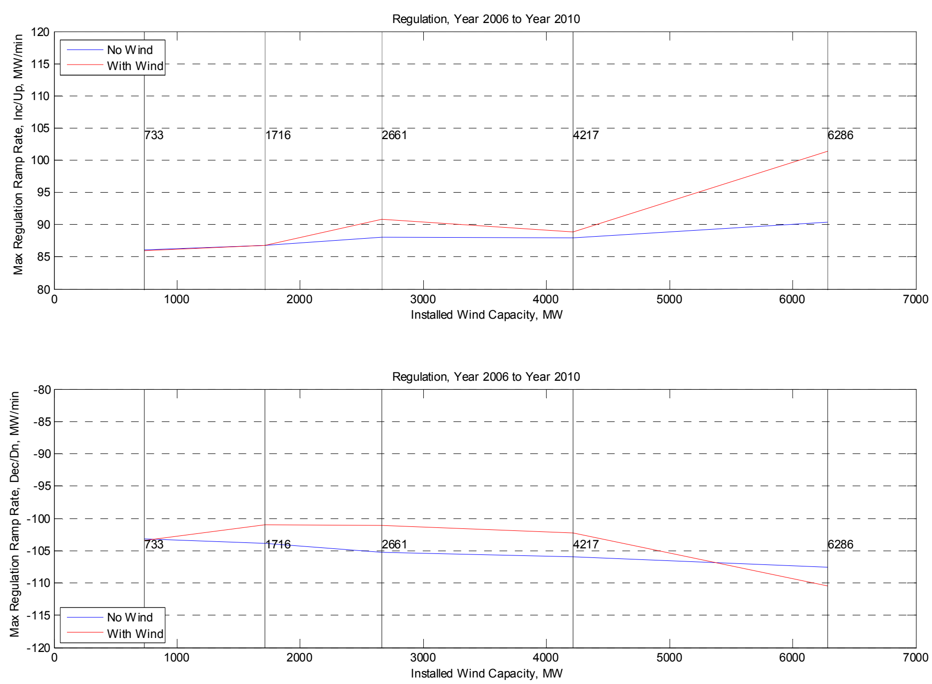


Figure IV. 36 Regulation ramp requirement for year 2006 through 2010

APPENDIX V

BPA WIND IMPACT STUDY RESULTS CONSIDERING NO FORECAST ERRORS

APPENDIX V: BPA WIND IMPACT STUDY RESULTS CONSIDERING NO FORECAST ERRORS

1. The following results were generated with forecast errors equal to zero in both load and wind forecasts:

    Use hourly average of actual load and wind as hour-ahead forecast;
    Use 10-min average of actual load and wind as real-time forecast.

(1) No wind

    Load following = LF_rt – LF_ha
    Regulation = L_a – LF_rt
    L_a: actual load;
    LF_ha: hour-ahead load forecast;
    LF_rt: real-time load forecast.

(2) With wind

    Load following = (LF_rt – LF_ha) – (WF_rt – WF_ha)
    Regulation = (L_a – LF_rt) – (W_a – WF_rt)
    W_a: actual wind generation;
    WF_ ha: hour-ahead wind forecast;
    WF_rt: real-time wind forecast.

2. All plots are using 5% for load following, 2.5% for regulation, and 5 MW swinging door deviation.

Plot set 1:

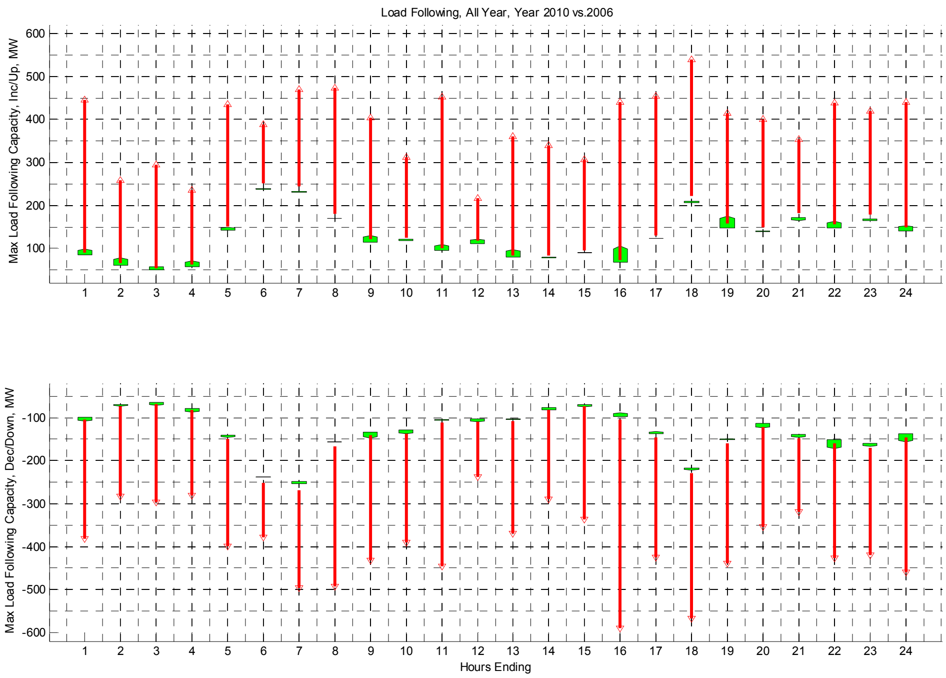


Figure V. 1 Load following capacity requirement in all year, year 2010 vs. 2006

Figure V. 2 Load following ramp requirement in all year, year 2010 vs. 2006

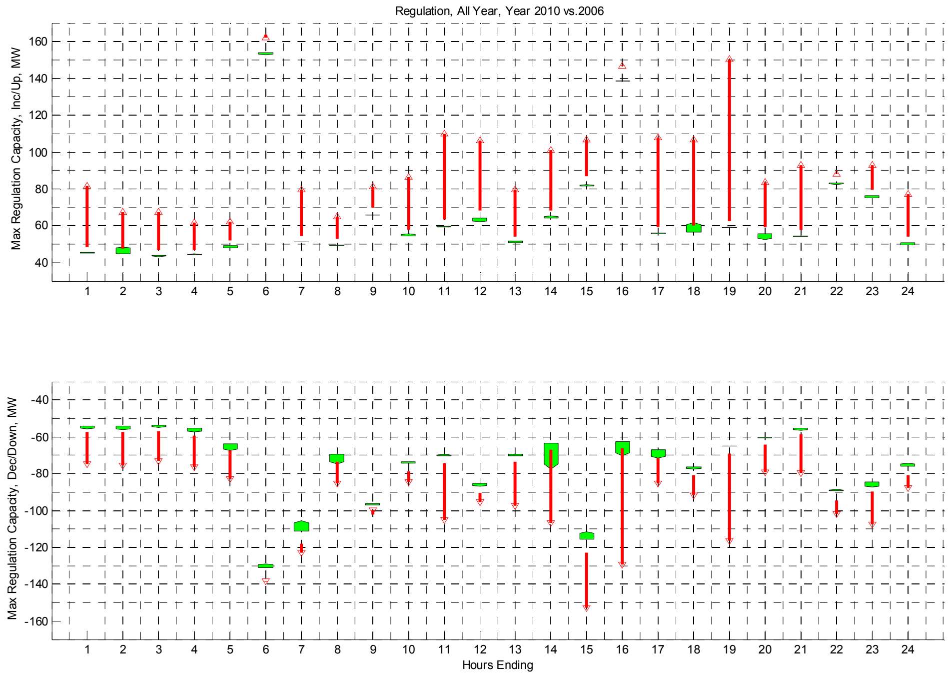


Figure V. 3 Regulation capacity requirement in all year, year 2010 vs. 2006

Figure V. 4 Regulation ramp requirement in all year, year 2010 vs. 2006

Plot set 2:

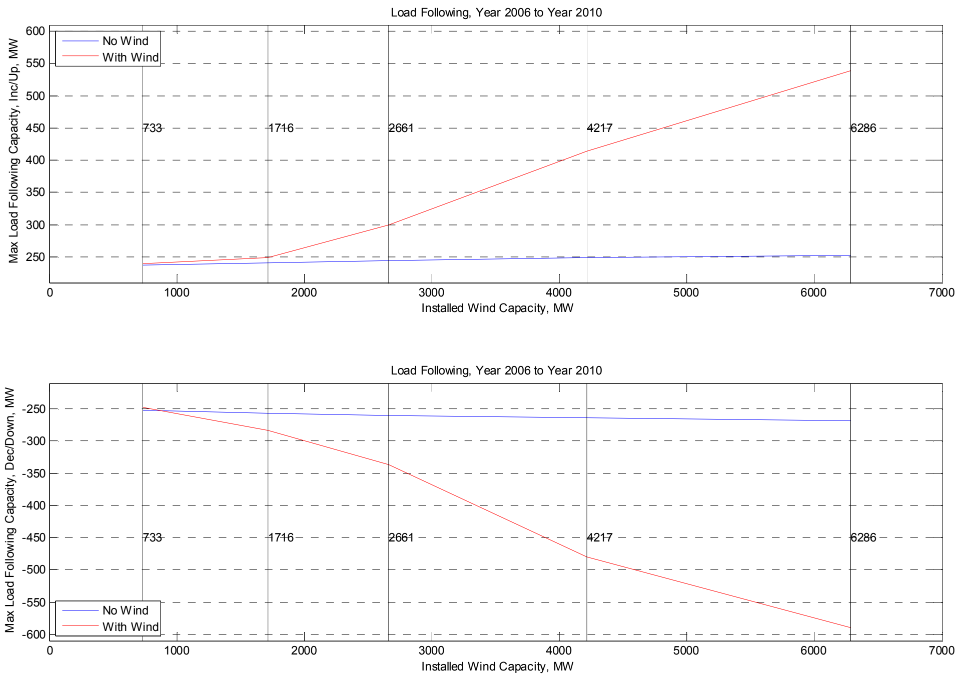


Figure V. 5 Load following capacity requirement for year 2006 through 2010

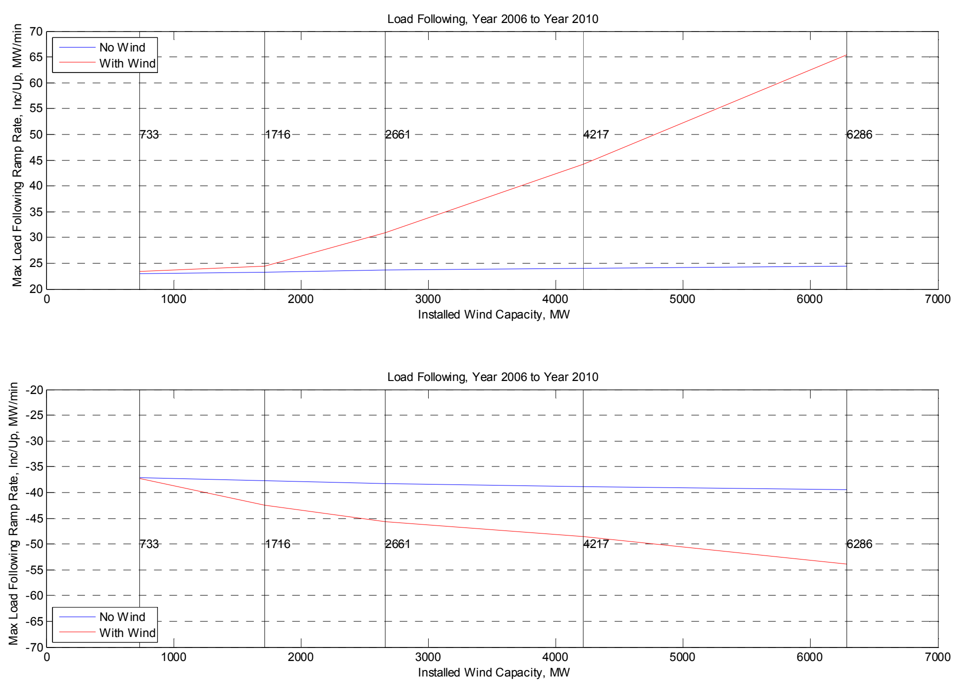


Figure V. 6 Load following ramp requirement for year 2006 through 2010

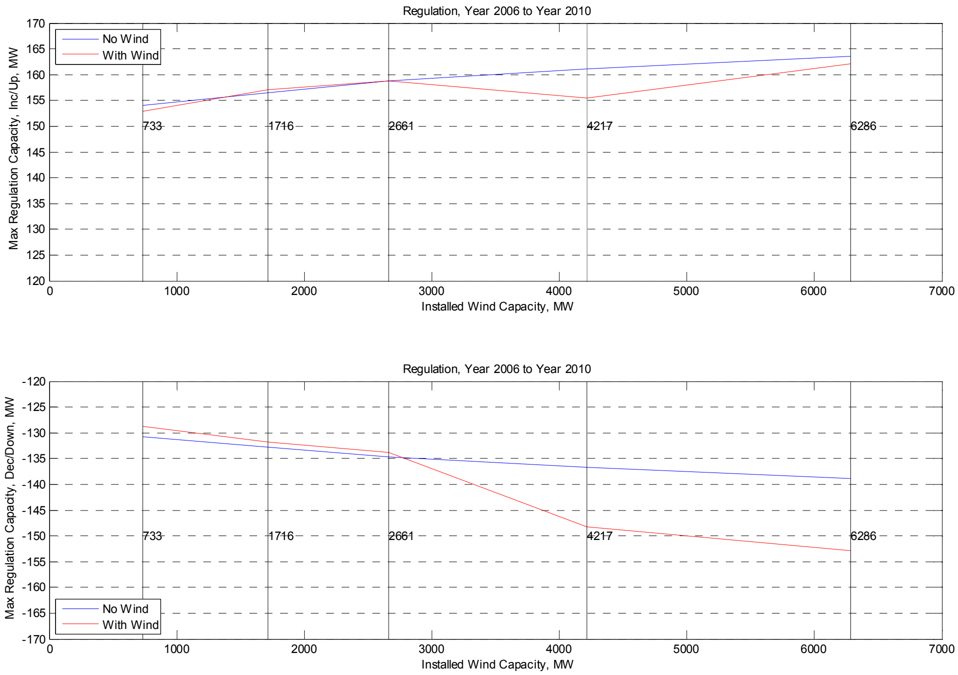


Figure V. 7 Regulation capacity requirement for year 2006 through 2010

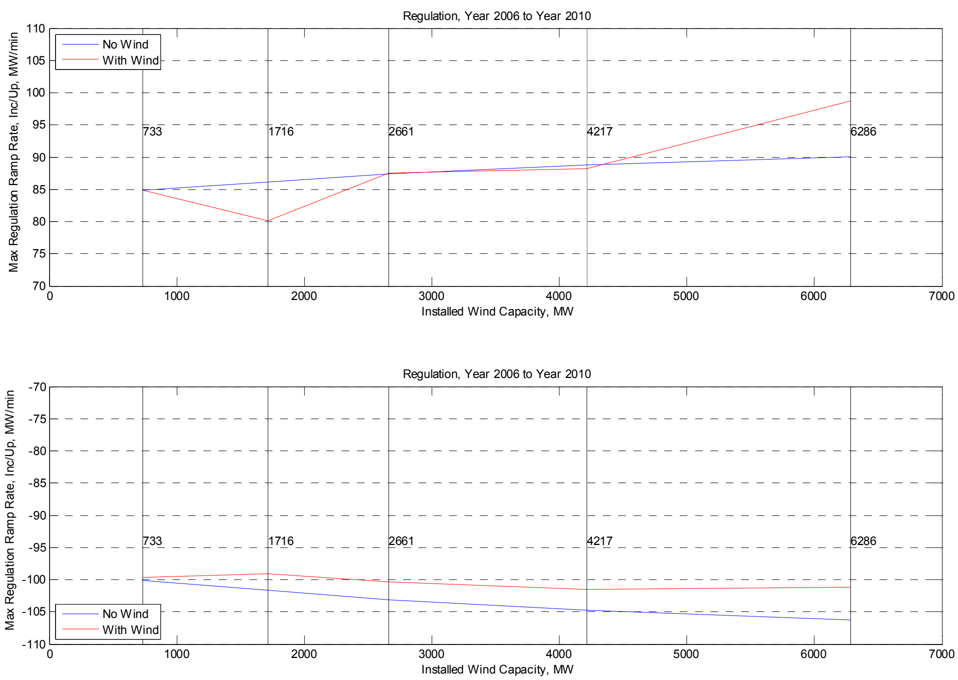


Figure V. 8 Regulation ramp requirement for year 2006 through 2010