KERMIT Study Report

To determine the effectiveness of the AGC in controlling fast and conventional resources in the PJM frequency regulation market

PJM Interconnection, LLC
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Prepared by KEMA Inc.
Chalfont, December 13, 2011

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1. Executive Summary

KEMA was engaged by PJM during the summer of 2011 to assist in the analysis of critical questions that PJM has about how to determine the effectiveness of the PJM AGC control algorithm for the traditional and dynamic (“fast”) regulation control signals and the impact of various levels of fast-following resources selected to provide regulation services in the PJM market. KEMA offered to conduct a study leveraging the use of KEMA’s Renewable Model Integrating Technologies toolkit and methodology. The effort is now complete and this report presents the results of the study.

PJM set a short list of goals for the study that were used by KEMA to customize the KERMIT methodology and tool for the purpose of the study:

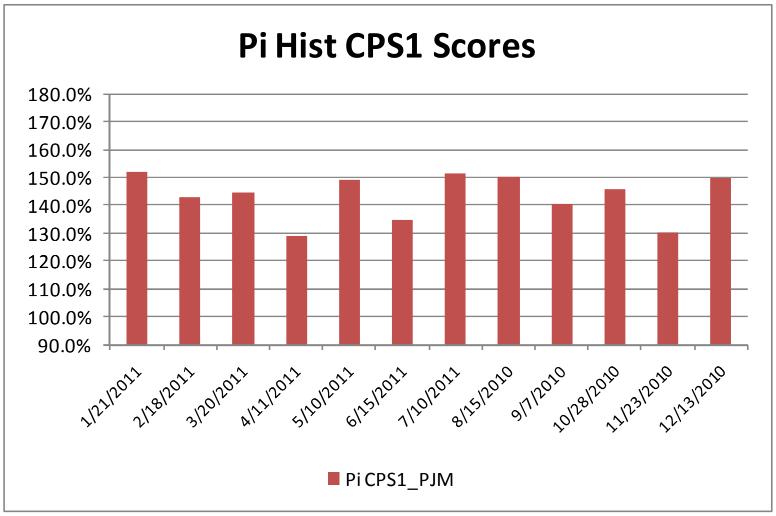
1) Establish a platform for these and other long term dynamics / system regulation and frequency response studies of the PJM system and its resources by developing a KERMIT model implementation of the PJM system and calibrating it to observed real time data

2) Examine the relative performance and impact on system performance of fast versus traditional regulation resources

3) Simulate and analyze the metric of MW-mileage and response accuracy for resources with different responses to the PJM regulation control signals.

1.1 Key Findings and Conclusions:

1) CPS1 compliance requires the score to be above 100% and PJM traditionally stays well above the 100% score. PJM’s current regulation requirement is 1% of the peak load for peak hours and 1% of the minimum load for the off-peak hours. PI-historian data provided by PJM for the 12 representative dates of the year shows that CPS1 is generally very high, averaging 143.4% using current regulation requirements.



2) Based on the simulations, the addition of faster regulation resources in 5% increments (from 5% to 50% of the regulation requirement), improved the average CPS1 scores for all studied dates, when compared to the base case simulation results and while keeping the same regulation requirements as in present practice.

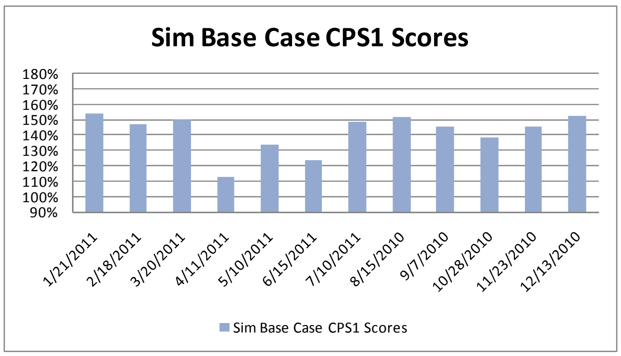
3) Closer examination of each simulation through the use of contour plots (see Table 3 in Section 5.2.1) suggests that CPS1 performance can be maintained near historical levels while reducing the regulation requirements. The table below summarizes the relationship between increased fast resources and decreased regulation requirements while keeping the CPS1 scores consistent. These plots also indicate diminishing returns for levels of fast resources beyond the percentages indicated below.

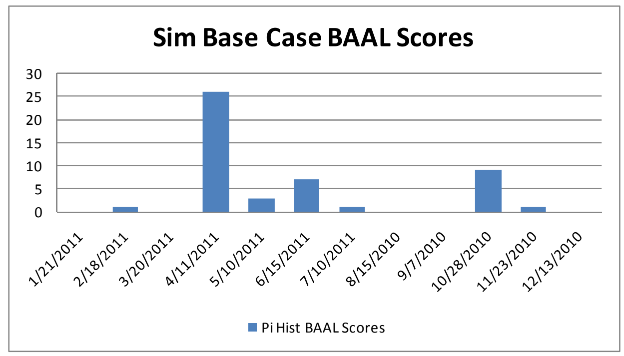
Combinations of Reg Req and Increased Fast Resources needed to maintain the same CPS1 Performance as Pi)

Date	CPS1 Target	Reg Req	Fast Res % of Reg Req
1/21/2011	154%	0.45%	30%
2/18/2011	147%	0.45%	35%
3/20/2011	150%	0.63%	25%
4/11/2011	113%	0.85%	20%
5/10/2011	134%	0.86%	20%
6/15/2011	124%	0.90%	10%
7/10/2011	148%	0.57%	15%
8/15/2010	151%	0.45%	25%
9/7/2010	145%	0.55%	15%

10/28/2010	138%	0.85%	20%
11/23/2010	145%	0.55%	30%
12/13/2010	152%	0.52%	20%

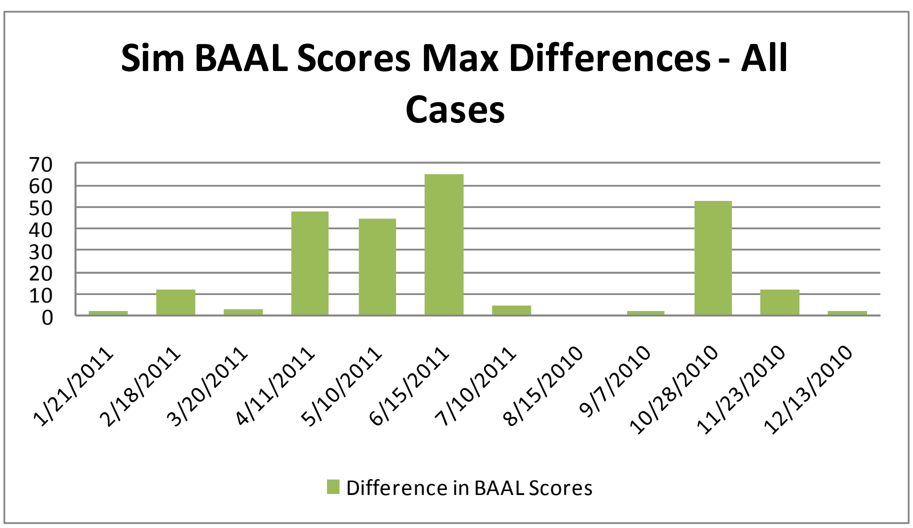
4) Under base case conditions (i.e., 1% Regulation Requirement and no fast resources providing regulation), when the CPS1 is already very high, the BAAL violations tend also to be low. However, when CPS1 is closer to the lower ranges, BAAL violations tend to increase more quickly than CPS1 decreases.





5) The general effect on the BAAL metric caused by decreasing regulation requirements and increasing fast resources participation in regulation tends to increase the number of BAAL violations (See the heat map charts in Table 6 of the report).

6) The degree with which the BAAL worsens appears to be aligned with the days with lower CPS1 scores.



For the days that have lower CPS1 scores (April, May, June and October), the differences in BAAL violations scores between the base case and the most aggressive scenarios are more extreme. These observations tend to support the idea that factors influenced by seasonality; i.e., load levels, load forecasting error, generation fleet availability and capability etc. need to be taken into account before committing to changes in regulation requirements.

7) The pay for performance findings as based on the KEMA MW-mile calculation approach may serve as an input to PJM staff in their continued consideration of their performance scores. As such, the results presented in this report illustrate certain principles used in the KEMA formulation, such as using a higher order formulation to measure the “MW-miles traveled“ by resource when responding to PJM regulation signals.

2. Introduction

KEMA was engaged by PJM during the summer of 2011 to assist in the analysis of critical questions that PJM has about how to determine the effectiveness of the PJM AGC control algorithm for the traditional and dynamic ("fast") regulation control signals and the impact of various levels of fast-following resources selected to provide regulation services in the PJM market. KEMA offered to conduct a study leveraging the use of KEMA's Renewable Model Integrating Technologies toolkit and methodology.

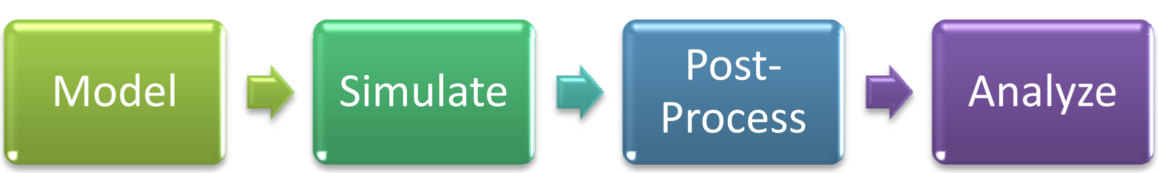
3. Study Goals

Based on PJM needs to further understand the impact of adding larger numbers of fast frequency regulation resources, PJM established the following goals for this KEMA study:

- Establish a platform for these and other long term dynamics / system regulation and frequency response studies of the PJM system and its resources by developing a KERMIT model implementation of the PJM system and calibrating it to observed real time data.
- Examine the relative performance and impact on system performance of fast versus traditional regulation resources
- Simulate and analyze the metric of a "MW mileage" or pay for performance tariff for regulation services that can differentiate between resources with different response rates
- Simulate and analyze the PJM "response accuracy" metric and simulate the effectiveness of this metric for different scenarios of unit response and non-response.

These goals where therefore converted into a series of tasks and activities that followed the sequence shown in Figure 1.

Figure 1: Study Sequence



4. Tools and Methodology

Since the introduction of the KEMA process for studying the varying effects of renewable resources on bulk power systems, that process has evolved into a repeatable methodology that is both structured, but also flexible and highly customizable. As in any other power system modeling exercise, the key to reliable results is a credible model of the power system based on the most reliable data available to describe the physical system targeted for the study. The methodology is presented in Figure 1.

In order to study frequency regulation dynamics and other power system behaviors in the real time timeframe, KEMA developed a unique tool to allow an easier and more flexible exploration of the real time behavior of power systems in terms of system frequency observations, computation of Area Control Error, Control Performance Standards 1 and 2 and several other metrics designed to understand the predicted behavior of the modeled system. This tool and methodology are combined into the KEMA Renewable Model Integrating Technologies or KERMIT.

4.1 Devising scenarios and running simulation cases

After consultation with PJM staff, two input variables were selected to be changed independently for each of 12 study dates from each month of the year representing PJM on-peak and off-peak days valley: The PJM Regulation Requirement per hour and the percent of fast frequency regulation resources represented in the study by different combinations of Energy-Storage[1] technologies. The idea was to gain insights into the tradeoff between the two. Intuitively, one can expect that it is possible to reduce the regulation requirement by allowing for a higher level of fast frequency regulation resources to provide the required regulation service. This study is aimed at quantifying that trade-off.

Normally, the PJM Regulation Requirement for any of the 12 days is set to be 1% of the peak load for on-peak hours and 1% of the minimum load for the off-peak hours. In KERMIT a simplified approach was used as follows: For each day, the signal TRegA is set to 1% of minimum load from hour 00:00 to 05:00, and to 1% of maximum load between 05:00 and 24:00.

[1] Lithium Ion Battery Energy Storage systems and Flywheel Energy Storage systems were modeled in this study. That choice was given by the parallel study on emission impacts for the same scenarios being prepared for the Sandia National Laboratories.

This results in a step change in TRegA that occurs at hour 05:00. (-TRegA and +TRegA act as the lower and upper bounds for RegA.)

Each scenario looks at a different level with which fast-following resources provide regulation service. The notation is as follows.

- In the base case, the conventional resources respond fully (100%) to the signal RegA, and there is no fast resources providing regulation (0%)[2].
- When the conventional resources are said to provide 75% of regulation, they are responding to 0.75 RegA. The residual 25% of regulation is provided by fast resources following the control signal equal to RegD*(0.25*Regulation).

There are different ways to control storage; this study used the RegD signal, which already exists in PJM operation today.

The two variables that were manipulated in the combinations:

a. Vary the Regulation Requirement from 1.00% of peak load (or minimum load) down to 0.50% in 0.05% decrements. There are 11 possible points.

b. Vary the Conventional to Fast Regulation Resources mix from 100% to 50% in 5% decrements. There are 11 possible points.

Therefore, for each day, there are 11*11 = 121 scenarios. Since the study covers 12 days, the resulting number of scenarios studied was 1,452.

4.2 Post-Processing of simulated time-series

After all simulation cases were completed, selected output time-series (waveforms) were processed by the post-processing module of KERMIT to produce the metrics of interest. The metrics of interest are: Control Performance Standard 1 (CPS1), Balancing Authority ACE Limits (BAAL), and Pay for Performance metric based on the MW-mile concept.

[2] In reality PJM has two fast regulation participating devices enrolled in frequency regulation in the system but their current capacity is negligible to these results.

4.2.1 The CPS1 Metric

In the case of CPS1, PJM provided KEMA with the latest reference documents from NERC together with the specific parameter values that are in use today.[3]

4.2.2 The BAAL Metric

In the case of BAAL, PJM also provided KEMA with an Excel-based template that performs the BAAL calculations.[4] KEMA consulted the relevant NERC documents, provided by PJM, for how BAAL is defined and calculated, and wrote the Matlab® code for data processing. This Matlab® code was validated using PJM's Excel-based BAAL template as the benchmark.

4.2.3 The Pay for Performance Metric

Unlike CPS1 and BAAL, which are standard metrics, the Pay for Performance MW-mile metric is yet to be defined and widely adopted by the industry. For the purpose of this study, PJM asked KEMA to develop and propose a new algorithm that would define the MW-mile metric in a manner consistent with FERC's recent Notice of Proposed Regulation on the subject. PJM would use the results obtained by the KEMA MW-mile metric proposal to compare it with PJM's own pay-for-performance proposal in order to further understand the performance of PJM generation units and their expected response to PJM regulation control signals.

There are two components to KEMA's MW-mile metric. First, there is a MW-mile component that measures how far a unit traveled during a period of time. Second, there is a performance component that measures how closely a unit followed the AGC signal it received. KEMA proposed for each time instance (every 4 seconds) to keep track of the change in AGC power provided by a unit from one time instance to the next. Mathematically this is defined as follows:

$$\delta = Power_{t+1} - Power_t$$

We use δ_l to denote the MW-miles of the AGC signal sent to a generator and δ_r to denote the MW-miles of a generator in response to its AGC signal. Ideally δ_i and δ_r are the same but in reality they differ and a function is needed to measure the closeness between the signal that the generator receives from the AGC (δ_i) and the response of the unit (δ_r) to the input signal. In

[3] http://www.nerc.com/files/BAL-001-0_1a.pdf

[4] http://www.nerc.com/docs/standards/sar/BAL-007-011_pre-ballot_clean_05Sep06.pdf

other words, a function is needed to measure the performance of a unit in meeting its AGC signal. There are many ways to define such function; in this study, KEMA proposed the following definition:

$$f(\delta_i, \delta_r) = \begin{cases} 0 & \text{when} \quad |\delta_r| > 2|\delta_i| \\ \dfrac{2|\delta_i| \cdot |\delta_r| - \delta_r^2}{|\delta_i|} & \text{when} \quad 0 < |\delta_r| < 2|\delta_i| \end{cases}$$

Next, recognizing that each resource takes some time to respond, there needs to be an "anticipated response time", denoted as τ, for an acceptable delay between the two signals (δ_i) and (δ_r).

The Pay for Performance payment PP_{Total} (in $) is then defined to be the sum of the individual performance payments over all AGC time intervals:

$$PP_{Total} = \sum_{t=\tau}^{T} P_t * Q_t$$

where P_t is the price for each instant t, Q_t is the amount or quantity determinant for each instant t given by the $f(\delta_i\ \delta_r)$ function, and T represents the entire AGC time interval.

This definition was reviewed with PJM staff, which then provided KEMA with historical operational data for the purpose of testing and understanding the results implied by this definition of a MW-mile metric. The accuracy and time delay are consistent with the PJM performance score; however, this method lacks the use of the precision component which is part of the PJM performance score.

5. Findings and Conclusions

5.1 The Calibrated PJM Model for KERMIT

Since the historical performance of the chosen 12 days is known, they are used to benchmark the KERMIT model. Note that it is not possible in modeling to have the simulated waveforms to match the historical waveforms point-by-point; however, it is an acceptable practice to compare the two waveforms based on several macro-level metrics.[5] KEMA and PJM agreed upon the following metrics: CPS1, CPS2, average frequency, max of ACE, standard deviation of ACE. After a number of calibrations, the end results for the base-case waveforms are presented in Table 1.

All simulation cases are based on the calibrated parameters of the model. Subsequent simulation cases (over 1,400 such) are merely repetition of the base-case simulation where only two particular parameters are changed from case to case. The outputs are presented in Subsections 5.2.1 and 5.2.3.

Based on the comparison of these simulated results against Pi-Historical data, PJM and KEMA concluded that the KERMIT model developed for the study is a good representation of the PJM power system for studying frequency control dynamics.

[5] Each waveform has many data points as it spans 24 hours and has time resolution of every few seconds. It is impossible to match the simulation with the physical measurements point by point. Thus, a set of metrics are used to judge the goodness of the match on a macro level. Such method attempts to summarize an entire waveform as a single number—a metric.

Table 1: Comparison of actual waveforms and calibrated KERMIT waveforms.

DAY	Base Cases	Date	Reg. Req'mnt	CPS1	CPS2	Frequency Average (Hz)	Frequency 95% Percentile (Hz)	ACE_Max (MW)	ACE_Std Dev. (MW)
1	1-21-2011_Base_100PctReg	01-21-2011	1.00%	153.6%	95.8%	59.9999	60.0197	1035	272
	1-21-2011_PiHist	01-21-2011	1.00%	152.0%	93.1%	59.9988	60.0200	1294	280
2	2-18-2011_Base_100PctReg	02-18-2011	1.00%	146.9%	95.8%	59.9999	60.0205	1186	285
	2-18-2011_PiHist	02-18-2011	1.00%	143.1%	88.2%	60.0000	60.0300	1294	294
3	3-20-2011_Base_100PctReg	03-20-2011	1.00%	150.1%	91.0%	60.0000	60.0280	1272	308
	3-20-2011_PiHist	03-20-2011	1.00%	144.5%	91.0%	59.9994	60.0255	1506	283
4	4-11-2011_Base_100PctReg	04-11-2011	1.00%	112.6%	84.7%	59.9999	60.0311	2302	398
	4-11-2011_PiHist	04-11-2011	1.00%	129.2%	90.3%	60.0012	60.0310	1366	307
5	5-10-2011_Base_100PctReg	05-10-2011	1.00%	134.0%	82.6%	59.9998	60.0303	1697	380
	5-10-2011_PiHist	05-10-2011	1.00%	149.0%	88.9%	60.0007	60.0260	1080	277
6	6-15-2011_Base_100PctReg	06-15-2011	1.00%	123.6%	77.1%	59.9998	60.0314	1871	386
	6-15-2011_PiHist	06-15-2011	1.00%	134.8%	85.4%	59.9988	60.0250	1336	330
7	7-10-2011_Base_100PctReg	07-10-2011	1.00%	148.2%	87.5%	59.9999	60.0221	1339	305
	7-10-2011_PiHist	07-10-2011	1.00%	151.7%	89.6%	59.9974	60.0220	1770	312
8	8-15-2010_Base_100PctReg	08-15-2010	1.00%	151.5%	95.1%	60.0000	60.0218	1015	273
	8-15-2010_PiHist	08-15-2010	1.00%	150.5%	86.1%	60.0014	60.0251	956	266
9	9-7-2010_Base_100PctReg	09-07-2010	1.00%	145.2%	91.7%	59.9999	60.0232	1141	292
	9-7-2010_PiHist	09-07-2010	1.00%	140.4%	85.4%	59.9994	60.0240	1395	318
10	10-28-2010_Base_100PctReg	10-28-2010	1.00%	138.2%	81.9%	59.9999	60.0312	2161	403
	10-28-2010_PiHist	10-28-2010	1.00%	145.5%	82.6%	60.0016	60.0263	1306	291
11	11-23-2010_Base_100PctReg	11-23-2010	1.00%	145.2%	95.1%	60.0000	60.0214	1222	290
	11-23-2010_PiHist	11-23-2010	1.00%	130.2%	92.4%	59.9984	60.0279	2197	311
12	12-13-2010_Base_100PctReg	12-13-2010	1.00%	152.0%	92.4%	59.9999	60.0199	1132	279
	12-13-2010_PiHist	12-13-2010	1.00%	149.6%	86.1%	59.9946	60.0220	1717	319

5.2 Summary of Operational Impacts for different scenarios of “fast” storage resources

Once the model was calibrated and validated, the main task was to establish the benefits of adding “fast” regulating resources for frequency regulation and identify if there are points of diminishing returns in replacing conventional resources with these “fast” resources. In addition the study would need to identify the value or benefit of adding those “fast” resources relative to conventional resources.

The study team decided on studying the changes in PJM’s Control Performance Standard 1 (CPS1) as the primary predictor of the benefit of introducing additional “fast” regulation resources in the system. CPS2 values were also calculated and results provided in the appendices to the report.

The next subsections discuss the findings for each of these observations and the three selected metrics.

In general the comparison between the Historical measures provided by PJM and the KERMIT predicted values across all the scenarios compares as follows:

Table 2: Summary Stats Between Historical and All KERMIT Cases

	CPS1_PJM	CPS2 PJM	Frequency Average (Hz)	Frequency 95% Percentile (Hz)	ACE_Max (MW)	ACE_Std. Deviation (MW)
Pi- Hist Stats						
	143.37%	88.25%	59.999306	60.025396	1434.637	299.146335
	0.081327	0.03168	0.0019619	0.00322535	331.1127	19.8812587
	129.20%	82.64%	59.994643	60.02	955.8948	266.249206
	152.00%	93.06%	60.001647	60.030998	2197.251	329.874032
KERMIT Stats (All Cases)						
Median	140.31%	82.88%	59.999863	60.023811	1608.914	336.587443
StdDev	0.22756	0.081169	0.2275603	0.00584383	502.8701	81.852271
Min	65.27%	56.94%	59.999607	60.013911	985.7039	230.357147
Max	169.12%	95.83%	60.000044	60.033862	2758.727	532.593426

Overall maximum and median values between the Pi history and all the simulations are comparable indicating that a large number of simulations compare similarly to the base case. The higher standard deviations and lower minimum values from the KERMIT simulations indicate that there are simulations scenarios that are extreme and there are combinations of higher storage penetrations and lower regulation requirements that would be less effective for operational control. This is confirmed by the detailed results and summarized for each studied date with the contour maps discussed next.

5.2.1 Summary of Simulation Results for PJM's Control Performance Standard 1 (CPS1) Metric

The simulation indicates the following:

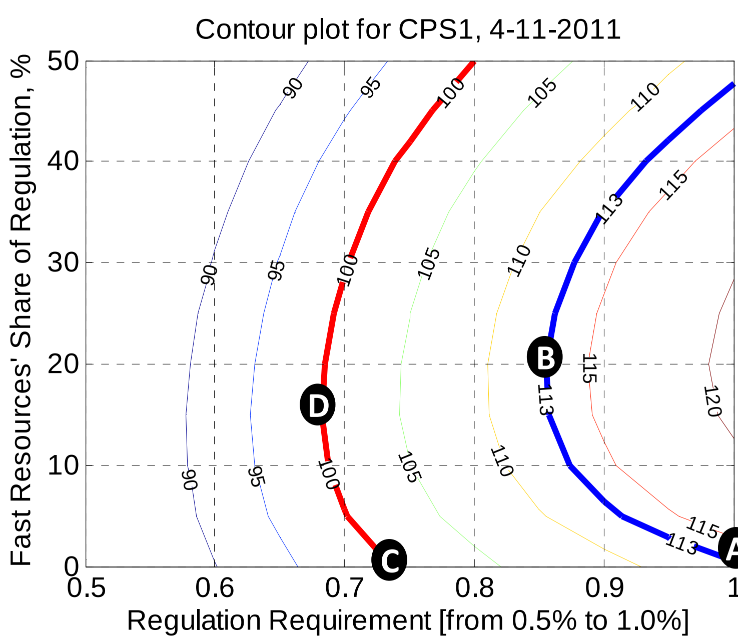
1) Based on the simulations, the addition of faster regulation resources in 5% increments (from 5% to 50% of the regulation requirement), improved the average CPS1 scores for all studied dates, when compared to the base case simulation results and while keeping the same regulation requirements as in present practice.

2) Closer examination of each simulation through the use of contour plots suggests that CPS1 performance can be maintained near historical levels while reducing the regulation requirements.

To support the above statements, the CPS1 metric was calculated for each of the scenarios and compared against the history of the CPS1 performance for the same day under base case conditions - no additional fast storage and 1% of peak or valley load as the regulation requirement of the PJM system. CPS1 values that correspond to the same day are grouped together in order to generate a contour plot of CPS1 values.

Such a contour plot is shown in Figure 2.

Figure 2: Simulated CPS1 Results for 4-11-2011



The contours provide insights into the trade-off between reducing the Regulation Requirement and increased use of Fast Resources. The curves in Figure 2 suggest that it is possible to reduce the Regulation Requirement while still being CPS1-compliant to a point.

A. The base case corresponds to x = 1.00% and y = 0%, and is denoted by ***Point A***. It is seen that the CPS1 value is 113%, and thus meets compliance at ***Point A*** (the base case). In fact, for all the 12 days, the CPS1 values are greater than 100%, thus compliance is always achieved.

B. It is possible to maintain the same level of CPS1 while reducing the Regulation Requirement. ***Point B*** indicates that Regulation Requirement can be reduced to 0.85%, under the condition that Fast Resources be used to provide regulation. The segment of the contour between point A and point B thus represents a meaningful trade-off between the two parameters. Cutting the Regulation Requirement to 0.85% or below begins to degrade CPS1, regardless of how many Fast Resources are added. ***Point B*** is an inflection point for Regulation Requirement

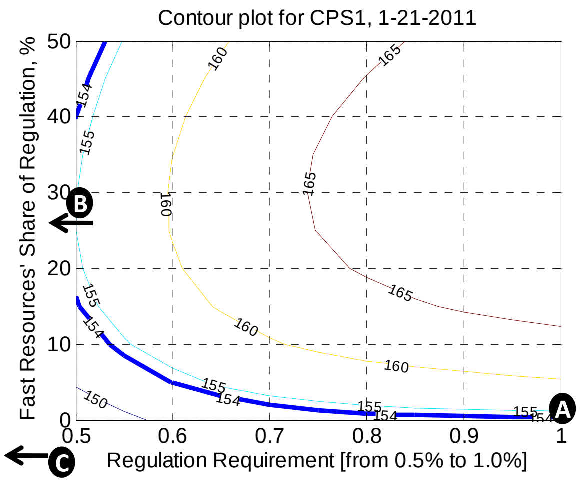
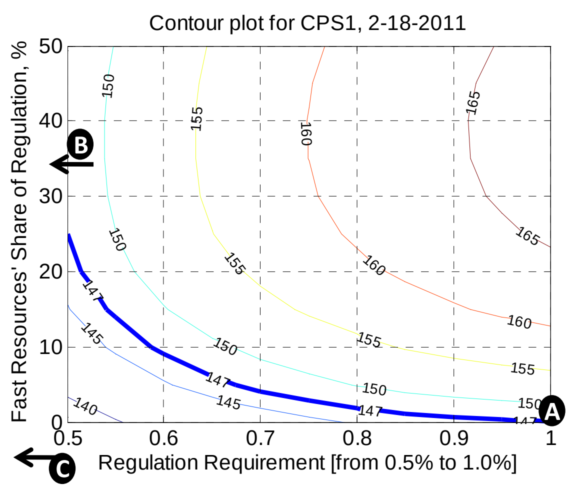
   The presence of an inflection point may seem counter-intuitive. However, recall that the simulation utilizes a control signal that is based on RegD, which is designed as a complement to the RegA signal and was not designed to carry all system regulation. Therefore, as increased fast-following resources enter the PJM system, the RegD algorithm will need additional modification. The issue of designing a control signal that can make best use of Fast Resources ("best" relative to a pre-defined set of metrics, such as CPS1) remains an open question and should be part of a follow-up study.

C. In this case, Figure 2 still suggests that to maintain minimum compliance (CPS1 = 100%) the minimum Regulation Requirement level would need to be no lower than 0.73% and is indicated by ***Point C***. Any attempt to reduce the Regulation Requirement further would result in CPS1 non-compliance for this specific date.

D. ***Point D*** represents the combination necessary for minimum CPS1 compliance; an extreme case used during the simulation to set the boundary conditions; a combination that is not recommended to ensure a reliable frequency regulation and system control. This is similar to ***Point C***, but the Regulation Requirement is even less than that of ***Point C***.

A contour plot was generated for each of the 12 days studied. Those plots are shown below in Table 3. A comparison of the results for Points B, C and D in those plots is show in Table 4.

Table 3: CPS1 Contour Plots Results

Graph	Comments
	January day A. Present: CPS1 = 154%. Regulation Requirement is 1%; No Fast Resources. B. To maintain the same CPS1=154%, Regulation Requirement can be reduced to 0.45%. Fast Resources are needed to provide 30% of regulation. C. To meet minimum compliance of CPS1=100%, Regulation Requirement can be reduced to less than 0.5% using only conventional resources.
	February day A. Present: CPS1 = 147%. Regulation Requirement is 1%; No Fast Resources. B. To maintain the same CPS1=147%, Regulation Requirement can be reduced to 0.45%. Fast Resources are needed to provide 35% of regulation. C. To meet minimum compliance of CPS1=100%, Regulation Requirement can be reduced to less than 0.5%; using only conventional resources.

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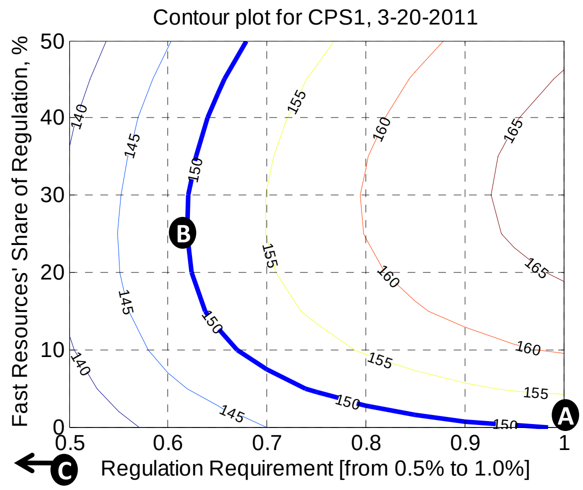

</td><td>
March day

A. Present: CPS1 = 150%. Regulation Requirement is 1%; No Fast Resources.
B. To maintain the same CPS1=150%, Regulation Requirement can be reduced to 0.63%. Fast Resources are needed to provide 25% of regulation.
C. To meet minimum compliance of CPS1=100%, Regulation Requirement can be reduced to less than 0.5 using only conventional resources.
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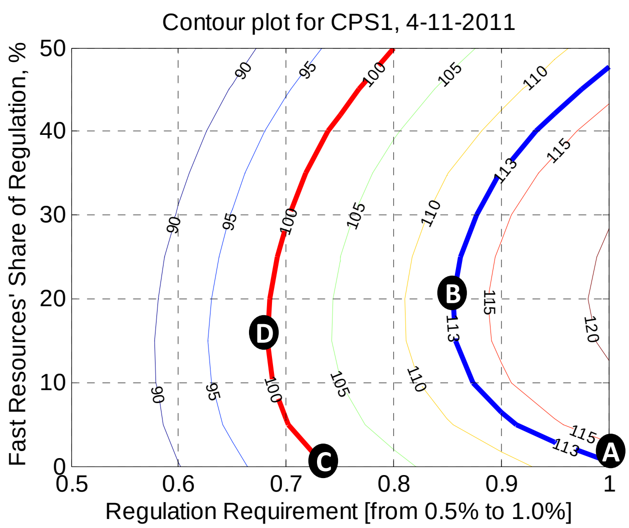

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April day

A. Present: CPS1 = 113%. Regulation Requirement is 1%; No Fast Resources.
B. To maintain the same CPS1=113%, Regulation Requirement can be reduced to 0.85%. Fast Resources are needed to provide 20% of regulation.
C. To meet minimum compliance of CPS1=100%, Regulation Requirement can be reduced to less than 0.73%; using only conventional resources.
D. To meet minimum compliance of CPS1=100%, Regulation Requirement can be reduced to 0.68% only if Fast Resources provide 20% of regulation.
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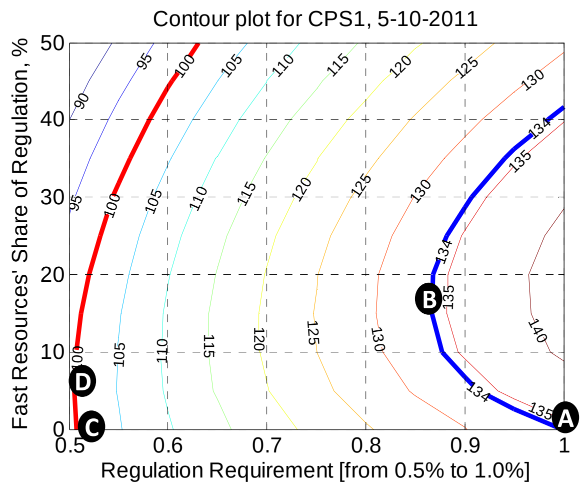

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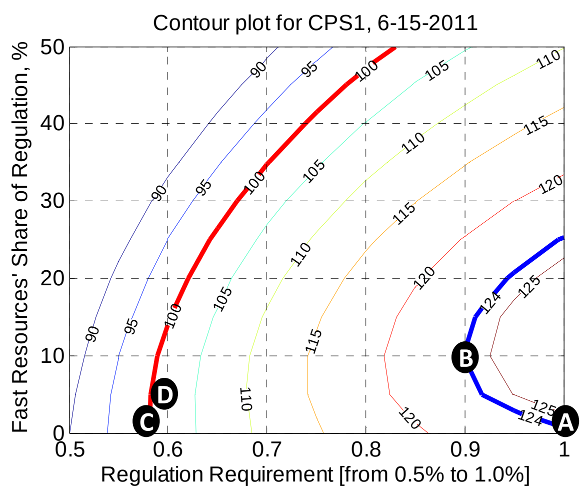
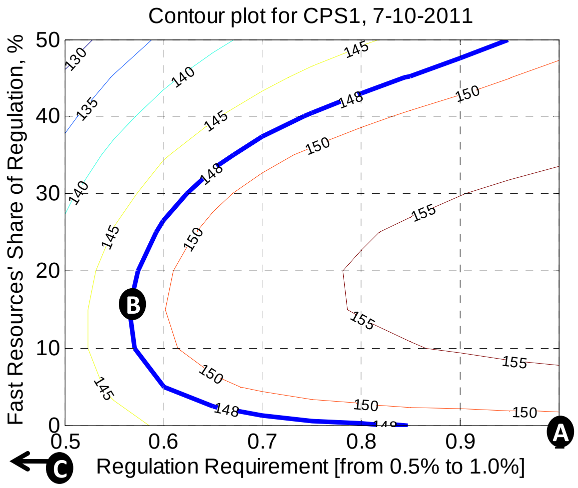
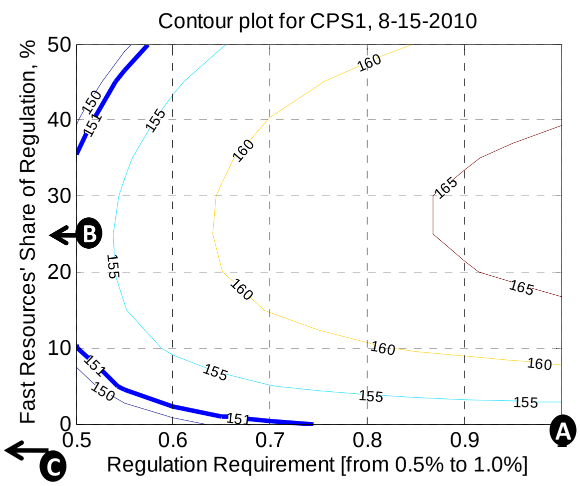
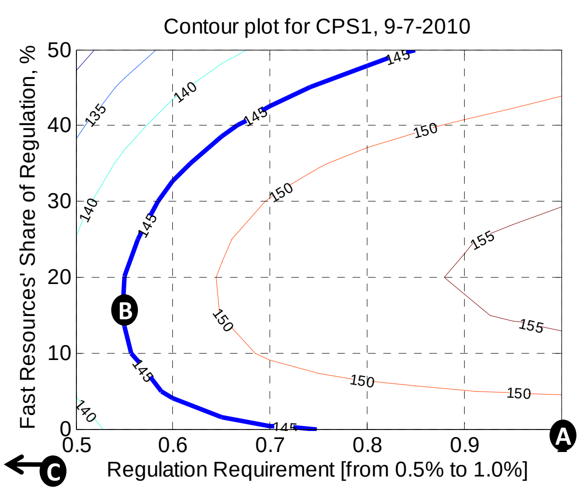
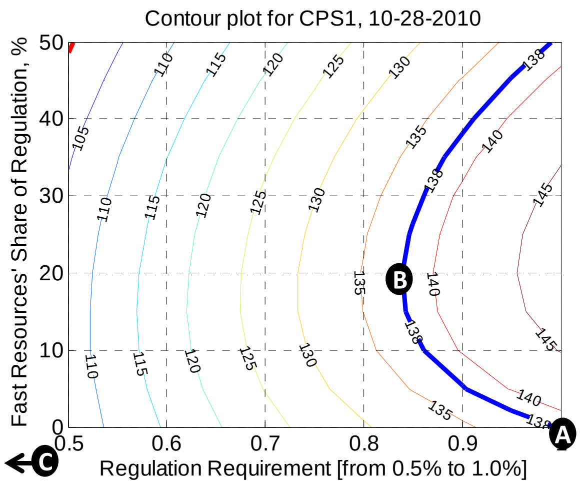
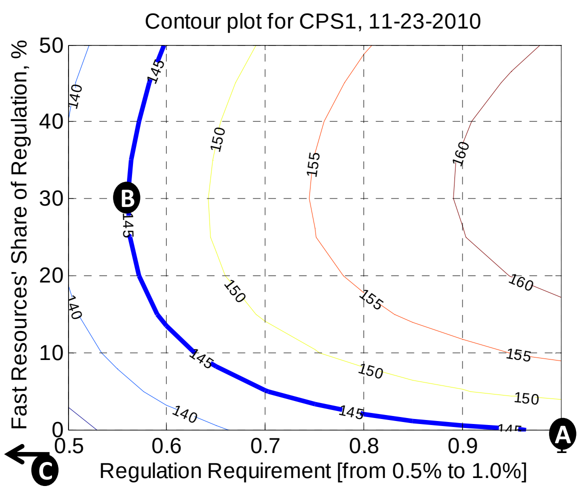
May day

A. Present: CPS1 = 134%. Regulation Requirement is 1%; No Fast Resources.
B. To maintain the same CPS1=134%, Regulation Requirement can be reduced to 0.86%. Fast Resources are needed to provide 20% of regulation.
C. To meet minimum compliance of CPS1=100%, Regulation Requirement can be reduced to 0.5%; using only conventional resources.
D. Same as B. Fast Resources provide no benefits at this level of Regulation.
</td></tr>
<tr><td>


</td><td>
June day

A. Present: CPS1 = 124%. Regulation Requirement is 1%; No Fast Resources.
B. To maintain the same CPS1=124%, Regulation Requirement can be reduced to 0.9%. Fast Resources are needed to provide 10% of regulation.
C. To meet minimum compliance of CPS1=100%, Regulation Requirement can be reduced to 0.59%; using only conventional resources.
D. Same as B; Fast Resources provide no benefits at this level of Regulation
</td></tr>
</table>

Graph	Comments
	July day A. Present: CPS1 = 148%. Regulation Requirement is 1%; No Fast Resources. B. To maintain the same CPS1=148%, Regulation Requirement can be reduced to 0.57%. Fast Resources are needed to provide 15% of regulation. C. To meet minimum compliance of CPS1=100%, Regulation Requirement can be reduced to less than 0.5%; using only conventional resources.
	August day A. Present: CPS1 = 151%. Regulation Requirement is 1%; No Fast Resources. B. To maintain the same CPS1=151%, Regulation Requirement can be reduced to 0.45%. Fast Resources are needed to provide 25% of regulation. C. To meet minimum compliance of CPS1=100%, Regulation Requirement can be reduced to less than 0.5%; using only conventional resources.
	September day A. Present: CPS1 = 145%. Regulation Requirement is 1%; No Fast Resources. B. To maintain the same CPS1=145%, Regulation Requirement can be reduced to 0.55%. Fast Resources are needed to provide 15% of regulation. C. To meet minimum compliance of CPS1=100%, Regulation Requirement can be reduced to less than 0.5%; using only conventional resources.

Graph	Comments
	October day A. Present: CPS1 = 138%. Regulation Requirement is 1%; No Fast Resources. B. To maintain the same CPS1=138%, Regulation Requirement can be reduced to 0.85%. Fast Resources are needed to provide 20% of regulation. C. To meet minimum compliance of CPS1=100%, Regulation Requirement can be reduced to less than 0.5%; using only conventional resources.
	November day A. Present: CPS1 = 145%. Regulation Requirement is 1%; No Fast Resources. B. To maintain the same CPS1=145%, Regulation Requirement can be reduced to 0.55%. Fast Resources are needed to provide 30% of regulation. C. To meet minimum compliance of CPS1=100%, Regulation Requirement can be reduced to less than 0.5%; using only conventional resources.

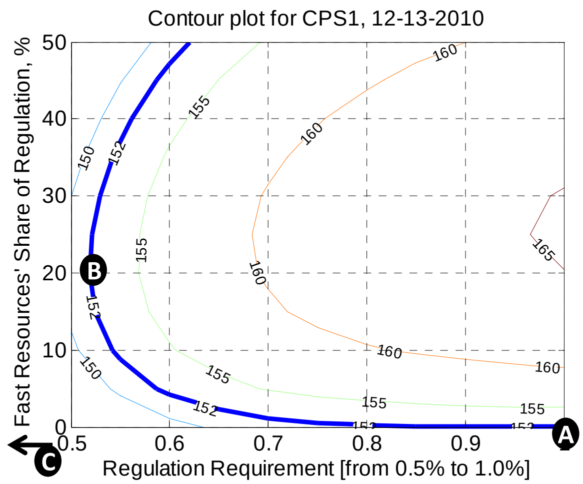
Graph	Comments
	December day A. Present: CPS1 = 152%. Regulation Requirement is 1%; No Fast Resources. B. To maintain the same CPS1=152%, Regulation Requirement can be reduced to 0.52%. Fast Resources are needed to provide 20% of regulation. C. To meet minimum compliance of CPS1=100%, Regulation Requirement can be reduced to less than 0.5%; using only conventional resources.

Table 4 below summarizes the key data points included in Table 3 for an easier comparison.

Table 4: KERMIT Simulation Contour Plots Results Range

	Point B (Same CPS 1 Performance as Pi)			Point C (Minimum Acceptable CPS1 Performance)			Point D (Alternative Reg Rq/Fast Res %)		
Date	CPS1 Target	Reg Req	Fast Res %	CPS1 Target	Reg Req	Fast Res %	CPS1 Target	Reg Req	Fast Res %
1/21/2011	154%	0.45%	30%	100%	0.50%	0%	Null	Null	Null
2/18/2011	147%	0.45%	35%	100%	0.50%	0%	Null	Null	Null
3/20/2011	150%	0.63%	25%	100%	0.50%	0%	Null	Null	Null
4/11/2011	***113%***	***0.85%***	***20%***	100%	0.73%	0%	100%	0.68%	20%
5/10/2011	134%	0.86%	20%	100%	0.50%	0%	100%	0.50%	0%
6/15/2011	*124%*	*0.90%*	*10%*	100%	0.59%	0%	100%	0.59%	0%
7/10/2011	148%	0.57%	15%	100%	0.50%	0%	Null	Null	Null
8/15/2010	151%	0.45%	25%	100%	0.50%	0%	Null	Null	Null
9/7/2010	145%	0.55%	15%	100%	0.50%	0%	Null	Null	Null
10/28/2010	138%	0.85%	20%	100%	0.50%	0%	Null	Null	Null
11/23/2010	145%	0.55%	30%	100%	0.50%	0%	Null	Null	Null
12/13/2010	152%	0.52%	20%	100%	0.50%	0%	Null	Null	Null

The following conclusions can be drawn from studying Tables 3 and 4:

1) All base-case points (Point A) reveal that PJM’s CPS1 compliance was very good across the selected days

2) The worst CPS1 score occurred under simulated conditions similar to those of the April 11, 2011 date (113%). For those conditions the simulation results indicate that to obtain that same CPS1 score or better, at least 20% of the Regulation Requirement needs to be provided by fast resources and the Regulation Requirement cannot be set below 0.85% of load. However, the results for the 6/15/2011 set of conditions indicate that at least in the near term, in order to preserve similar CPS1 compliance, the lowest acceptable Regulation Requirement is 0.9% when the system has at least 10% of that requirement assigned to fast resources under similar AGC control signals.

3) In the near term, the increased participation of fast resources as regulation providers show potential for benefits in the form of increased CPS1 scores. This additional margin in CPS1 performance can be used when considering the calculation of future regulation requirements without degradation of current CPS1 scores. However, the effective range is restricted as demonstrated by the inflection points (Point B’s on each day contour graph) when encountered. The reader must also keep in mind that all these simulation cases were based on the use of the PJM current AGC control design using the RegD

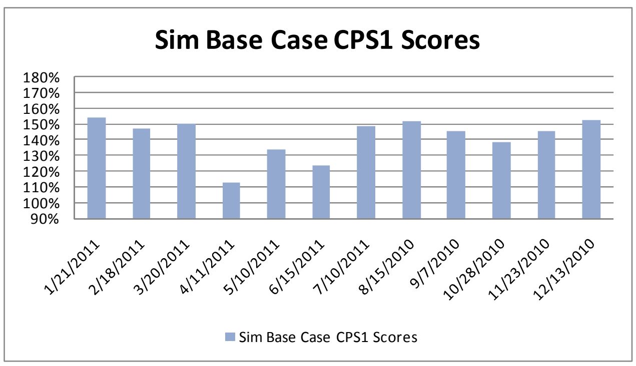
signal (and filters) to control the "fast" resources. Given the original purpose for using a RegD signal, further improvements could be made to allow additional fast resources participation by re-tuning the RegD signal and its filters if the regulation requirements are reduced to keep the CPS1 performance in compliance at similar historical levels.

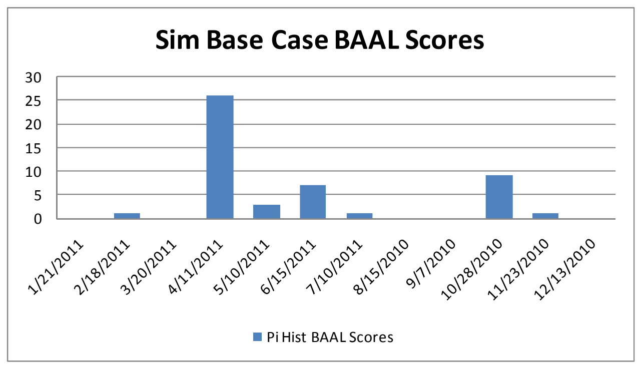
5.2.2 Results for the BAAL Performance Metric

With respect to the BAAL metric, the simulation outputs indicate the following:

1) Under base case conditions (i.e., 1% Regulation Requirement and no fast resources providing regulation), when the CPS1 is already very high, the BAAL violations tend also to be low. However, when CPS1 is closer to the lower ranges, BAAL violations tend to increase (Figure 3).

Figure 3: Simulation Base Case CPS1 and BAAL Scores

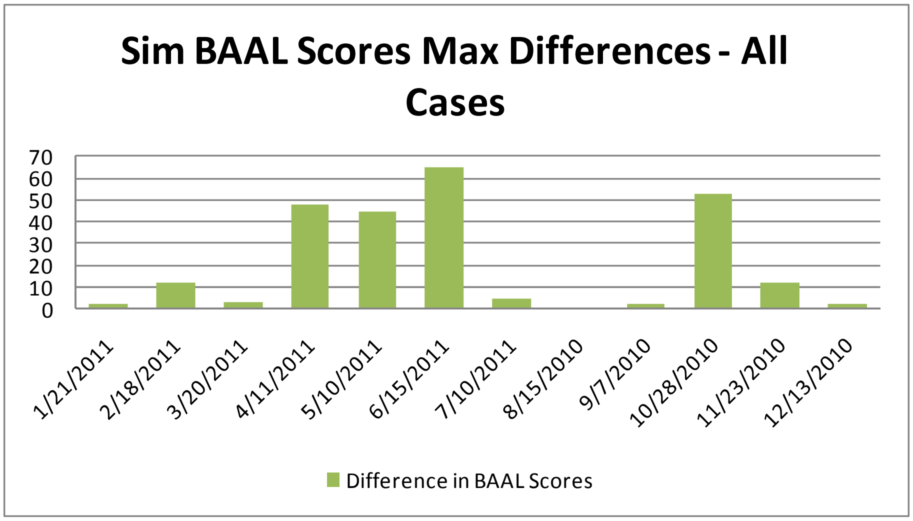




2) The general effect on the BAAL metric caused by decreasing regulation requirements and increasing fast resources participation in regulation tends to increase the number of BAAL violations (See the heat map charts in Table 5 of the report).

3) The degree with which the BAAL score worsen, appears to be aligned with the days with lower CPS1 scores (Figure 4).

Figure 4: Differences in Simulated BAAL scores between opposite scenarios (Base Case vs. Lowest Regulation Requirement / Highest Fast resources participation)



For the days that have lower CPS1 scores (April, May, June and October), the differences in BAAL violations scores between the base case and the most aggressive scenarios are more extreme. These observations tend to support the idea that factors influenced by seasonality; i.e., load levels, load forecasting error, generation fleet availability and capability etc. need to be taken into account.

The detail analysis to support the above statements is given next.

The BAAL (Balancing Authority ACE Limits) metric requires the calculation of two time-varying thresholds $BAAL_{Low}$ and $BAAL_{High}$. At any time the ACE signal falls outside BAAL's bands, a violation is counted.

For each simulated day, the number of BAAL violations is counted and tabulated against the control parameters (x=Regulation Requirement, and y=Fast Resources' Share of Regulation). The day of May-10-2011 is given as an example in Figure 5. The count of base-case BAAL violations is 3 and is located at the lower-right corner of the grid. It is seen that with decreasing Regulation Requirement and increasing Fast Resources' role in regulation, the number of BAAL violations increases. The figure uses a visualization technique called heat-map which uses light color for cells with least number of violations and dark color for cells with high violation count.

5-10-2011

Fast Resources' Share of Regulation →	0.50%	0.55%	0.60%	0.65%	0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
50%	48	43	38	31	28	25	22	18	13	10	9
45%	46	40	34	28	26	23	21	17	12	10	6
40%	45	37	32	27	26	21	19	16	12	7	6
35%	43	36	31	26	22	21	18	13	10	6	6
30%	41	36	29	25	22	20	16	12	9	6	6
25%	40	33	28	24	20	19	15	12	9	6	6
20%	39	33	28	22	19	18	12	11	9	6	5
15%	38	32	25	22	18	14	12	10	8	5	4
10%	36	29	25	23	16	14	11	10	7	5	3
5%	35	28	26	21	16	13	11	10	6	5	3
0%	34	28	24	20	16	12	11	9	6	4	3

Regulation Requirement (as % of Daily Load) →

Figure 5: Typical dependence of BAAL on the control parameters.

The numbers on the grid represents the number of violations. "Heat map" technique is used to aid visualization.

The heat map of BAAL violation counts for all the 12 days are summarized in Table 5

Table 5: Changes in BAAL violations, by day, due to different operating parameters.

Heat map is used for visualization, with light color (yellow) meaning the least number of violations and dark color (red) most number of violations.

1-21-2011

Fast Resources' Share of Regulation →	0.50%	0.55%	0.60%	0.65%	0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
50%	2	1	1	0	0	0	0	0	0	0	0
45%	2	1	1	0	0	0	0	0	0	0	0
40%	2	1	1	0	0	0	0	0	0	0	0
35%	2	1	1	0	0	0	0	0	0	0	0
30%	2	1	1	0	0	0	0	0	0	0	0
25%	2	1	1	0	0	0	0	0	0	0	0
20%	1	1	1	0	0	0	0	0	0	0	0
15%	1	1	1	0	0	0	0	0	0	0	0
10%	1	1	1	0	0	0	0	0	0	0	0
5%	1	1	1	0	0	0	0	0	0	0	0
0%	1	1	1	0	0	0	0	0	0	0	$\boxed{0}$

Regulation Requirement (as % of Daily Load) →

2-18-2011

Fast Resources' Share of Regulation →	0.50%	0.55%	0.60%	0.65%	0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
50%	13	11	7	3	2	2	2	2	2	1	1
45%	12	9	5	2	2	2	2	2	1	1	1
40%	10	7	3	2	2	2	2	2	1	1	1
35%	8	6	3	2	2	2	2	2	1	1	1
30%	8	4	3	2	2	2	2	1	1	1	1
25%	8	4	3	2	2	2	2	1	1	1	1
20%	5	4	3	2	2	2	2	1	1	1	1
15%	5	3	3	2	2	2	2	1	1	1	1
10%	5	3	3	2	2	2	1	1	1	1	1
5%	5	3	3	2	2	2	1	1	1	1	1
0%	5	3	3	2	2	2	1	1	1	1	$\boxed{1}$

Regulation Requirement (as % of Daily Load) →

3-20-2011

Fast Resources' Share of Regulation →	0.50%	0.55%	0.60%	0.65%	0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
50%	3	3	3	2	1	1	1	1	0	0	0
45%	3	3	3	2	1	1	1	0	0	0	0
40%	3	3	2	2	1	1	1	0	0	0	0
35%	3	3	2	1	1	1	0	0	0	0	0
30%	3	2	2	1	1	1	0	0	0	0	0
25%	3	2	2	1	1	1	0	0	0	0	0
20%	2	2	2	1	1	0	0	0	0	0	0
15%	2	2	2	1	1	0	0	0	0	0	0
10%	2	2	2	1	1	0	0	0	0	0	0
5%	2	2	2	1	0	0	0	0	0	0	0
0%	2	2	2	1	0	0	0	0	0	0	$\boxed{0}$

Regulation Requirement (as % of Daily Load) →

4-11-2011

Fast Resources' Share of Regulation →	0.50%	0.55%	0.60%	0.65%	0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
50%	74	68	66	63	62	59	57	54	52	50	46
45%	71	67	64	62	60	57	53	52	50	47	43
40%	70	66	62	58	56	54	53	51	46	44	42
35%	68	63	59	57	54	52	51	45	44	41	34
30%	67	61	58	56	51	51	46	44	40	36	32
25%	64	60	54	51	50	48	45	39	37	31	30
20%	61	57	51	50	48	45	40	36	35	29	28
15%	58	56	51	48	44	40	37	36	32	27	27
10%	58	53	50	44	41	40	38	34	29	27	27
5%	57	52	46	42	41	38	36	30	28	27	27
0%	55	50	43	41	38	38	36	30	28	27	$\boxed{26}$

Regulation Requirement (as % of Daily Load) →

5-10-2011

Fast Resources' Share of Regulation →	0.50%	0.55%	0.60%	0.65%	0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
50%	48	43	38	31	28	25	22	18	13	10	9
45%	46	40	34	28	26	23	21	17	12	10	6
40%	45	37	32	27	26	21	19	16	12	7	6
35%	43	36	31	26	22	21	18	13	10	6	6
30%	41	36	29	25	22	20	16	12	9	6	6
25%	40	33	28	24	20	19	15	12	9	6	6
20%	39	33	28	22	19	18	12	11	9	6	5
15%	38	32	25	22	18	14	12	10	8	5	4
10%	36	29	25	23	16	14	11	10	7	5	3
5%	35	28	26	21	16	13	11	10	6	5	3
0%	34	28	24	20	16	12	11	9	6	4	$\boxed{3}$

Regulation Requirement (as % of Daily Load) →

6-15-2011

Fast Resources' Share of Regulation →	0.50%	0.55%	0.60%	0.65%	0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
50%	72	66	62	58	54	43	37	34	28	22	18
45%	68	65	59	57	46	38	36	30	24	17	16
40%	68	63	57	49	42	37	33	26	20	15	13
35%	65	61	51	43	39	35	29	23	17	14	13
30%	63	55	47	40	36	32	25	18	16	13	13
25%	60	48	42	39	32	27	22	18	15	12	12
20%	55	46	41	36	29	25	21	18	14	12	8
15%	52	44	38	34	29	23	20	16	14	10	6
10%	51	43	35	32	25	23	20	15	12	8	8
5%	48	39	34	30	24	22	17	15	10	7	7
0%	45	37	33	27	24	21	17	13	9	7	$\boxed{7}$

Regulation Requirement (as % of Daily Load) →

7-10-2011

Fast Resources' Share of Regulation →	0.50%	0.55%	0.60%	0.65%	0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
50%	6	4	3	3	2	2	2	1	1	0	0
45%	5	3	3	3	2	2	2	1	1	1	0
40%	4	3	3	2	2	2	2	1	1	1	0
35%	4	3	2	2	2	2	2	1	1	0	0
30%	4	2	2	2	2	2	2	1	1	0	0
25%	3	2	2	2	2	2	2	1	0	0	0
20%	3	2	2	2	2	2	2	1	0	0	0
15%	3	2	2	2	2	2	1	1	1	1	0
10%	3	2	2	2	2	1	1	1	1	1	1
5%	3	2	2	2	2	1	1	1	1	1	1
0%	3	2	2	2	2	1	1	1	1	1	$\boxed{1}$

Regulation Requirement (as % of Daily Load) →

8-15-2010

Fast Resources' Share of Regulation →	0.50%	0.55%	0.60%	0.65%	0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
50%	0	0	0	0	0	0	0	0	0	0	0
45%	0	0	0	0	0	0	0	0	0	0	0
40%	0	0	0	0	0	0	0	0	0	0	0
35%	0	0	0	0	0	0	0	0	0	0	0
30%	0	0	0	0	0	0	0	0	0	0	0
25%	0	0	0	0	0	0	0	0	0	0	0
20%	0	0	0	0	0	0	0	0	0	0	0
15%	0	0	0	0	0	0	0	0	0	0	0
10%	0	0	0	0	0	0	0	0	0	0	0
5%	0	0	0	0	0	0	0	0	0	0	0
0%	0	0	0	0	0	0	0	0	0	0	$\boxed{0}$

Regulation Requirement (as % of Daily Load) →

9-7-2010

Fast Resources' Share of Regulation →	0.50%	0.55%	0.60%	0.65%	0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
50%	2	2	1	1	0	0	0	0	0	0	0
45%	2	1	1	1	0	0	0	0	0	0	0
40%	2	1	1	1	0	0	0	0	0	0	0
35%	2	1	1	0	0	0	0	0	0	0	0
30%	1	1	1	0	0	0	0	0	0	0	0
25%	1	1	1	0	0	0	0	0	0	0	0
20%	1	1	0	0	0	0	0	0	0	0	0
15%	1	1	0	0	0	0	0	0	0	0	0
10%	1	1	0	0	0	0	0	0	0	0	0
5%	1	0	0	0	0	0	0	0	0	0	0
0%	1	0	0	0	0	0	0	0	0	0	$\boxed{0}$

Regulation Requirement (as % of Daily Load) →

10-28-2010

Fast Resources' Share of Regulation →	0.50%	0.55%	0.60%	0.65%	0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
50%	62	57	57	52	43	38	33	29	27	22	20
45%	60	55	53	45	42	38	30	26	24	22	18
40%	58	54	51	45	41	35	27	25	22	19	17
35%	58	52	47	43	37	30	24	22	20	17	14
30%	54	47	45	40	33	29	23	20	17	17	13
25%	50	45	44	39	33	28	22	18	17	15	12
20%	49	45	43	38	33	26	19	19	17	15	11
15%	48	43	43	37	32	23	19	19	15	13	11
10%	45	43	41	36	28	22	19	16	15	13	9
5%	45	43	41	34	27	20	18	14	14	12	9
0%	45	42	37	32	25	20	16	14	12	11	$\boxed{9}$

Regulation Requirement (as % of Daily Load) →

11-23-2010

Fast Resources' Share of Regulation →	0.50%	0.55%	0.60%	0.65%	0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
50%	13	12	12	11	4	3	2	2	2	1	1
45%	13	12	12	7	3	2	2	2	2	1	1
40%	13	12	9	5	2	2	2	2	1	1	1
35%	13	9	5	4	2	2	2	2	1	1	1
30%	12	9	5	3	2	2	2	2	1	1	1
25%	10	7	3	3	2	2	2	1	1	1	1
20%	8	6	3	3	2	2	2	1	1	1	1
15%	7	5	3	3	2	2	2	1	1	1	1
10%	6	4	3	3	2	2	2	1	1	1	1
5%	6	4	3	3	2	2	1	1	1	1	1
0%	5	4	3	3	2	2	1	1	1	1	$\boxed{1}$

Regulation Requirement (as % of Daily Load) →

12-13-2010

Fast Resources' Share of Regulation →	0.50%	0.55%	0.60%	0.65%	0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
50%	2	2	2	1	1	0	0	0	0	0	0
45%	2	2	2	1	1	0	0	0	0	0	0
40%	2	2	2	1	1	0	0	0	0	0	0
35%	2	2	2	1	1	0	0	0	0	0	0
30%	2	2	1	1	1	0	0	0	0	0	0
25%	2	2	1	1	1	0	0	0	0	0	0
20%	2	2	1	1	1	0	0	0	0	0	0
15%	2	2	1	1	1	0	0	0	0	0	0
10%	2	2	1	1	1	0	0	0	0	0	0
5%	2	2	1	1	1	0	0	0	0	0	0
0%	2	1	1	1	1	0	0	0	0	0	$\boxed{0}$

Regulation Requirement (as % of Daily Load) →

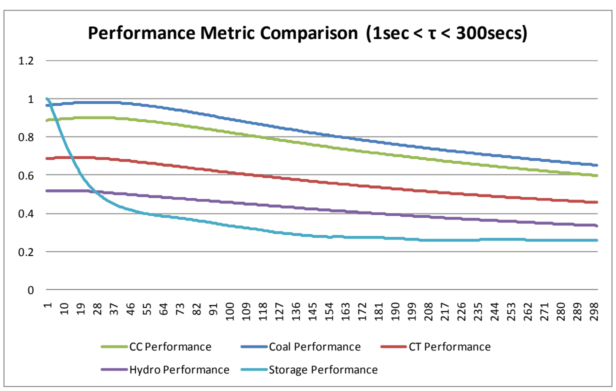
5.2.3 Results for Proposed MW-mile Calculation – 1/21/2010 Observations

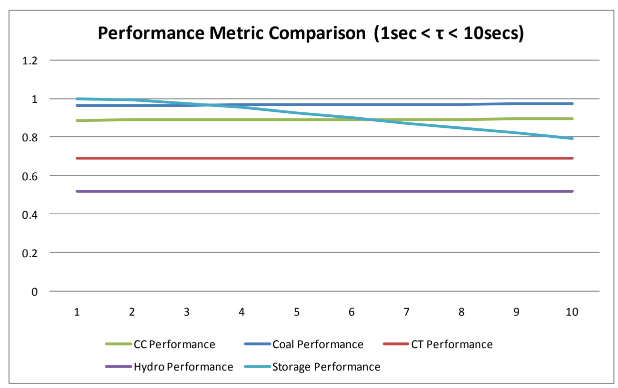
This section presents results for a small sample of conventional resources providing frequency regulation compared against a fast energy storage device providing frequency regulation. These results were obtained for a single day observation (1/21/2011) with a 25% energy storage penetration scenario. The MW-mile calculations were implemented in KERMIT post-processing and used to compare the performance and payments of a conventional resource against a fast regulation resource. The overall results for these calculations are included with Appendix C.

This MW-mile and performance mechanism provides a point of reference for the PJM performance calculations outlined in the draft manuals. This slightly different methodology allows a comparison of the results which can be used to highlight any concerns with a given calculation.

The performance results by unit type are extracted from this small sample and shown graphically in the Table 6:

Table 6: Performance Results for the MW-Mile Metric by Unit Type





The curves for each unit type in Table 6 are plotted against τ. Our proposed metric assumes that τ, the "anticipated response time" is known for the underlying resources in order to make meaningful comparison across different resource types.

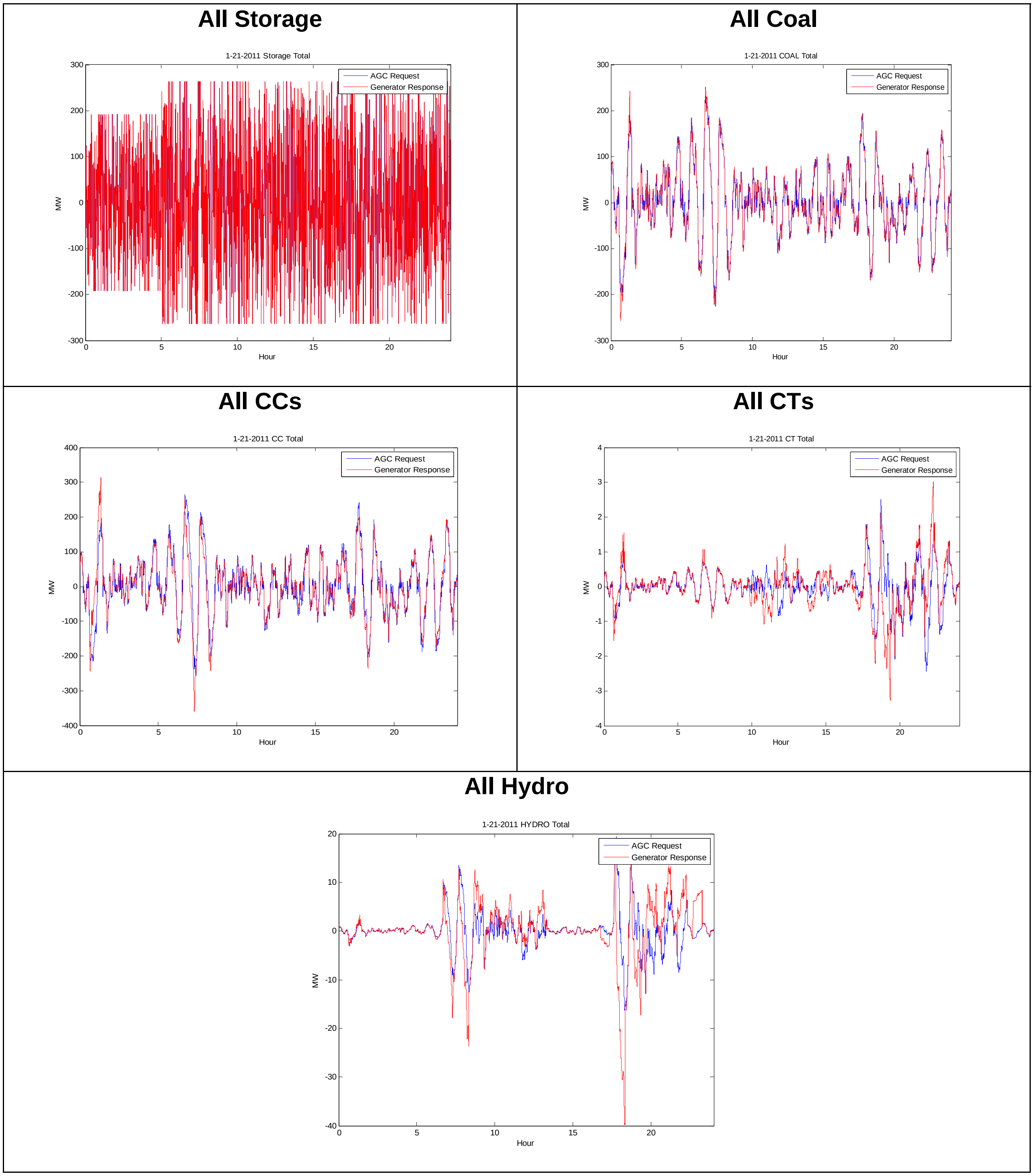
For Energy Storage, which has very short response time (τ is between 1 second and 3 seconds) their performance is near 1. This is consistent with the first curve in Figure 6 where the input and the response of "All Storage" appear to match each other well.

For conventional resources, the delays are longer (around 80 sec or more) and must be taken into account when reading the above chart. In this simulation, Coal and Combined Cycle are score relatively high; this is not too surprising because the time-series plots, second and third curves (All Coal and All CCs) of Figure 6, indicate that the response curve follows the control signal quite well. Combustion Turbine and Hydro both get a low score in the simulation; this is because the time-series plot (All CTs and All Hydro) reveal that there are periods of time during the 24-hour window, these two types of resources do not respond as asked.

Our example calculates the scores for the cumulative 24-hour period. This can of course be adopted for hour-by-hour scoring. In which case, CT and Hydro would get high scores in some hours, but low scores for the rest of the day as suggested by the response signals in Figure 6.

Another telling data set from this part of the study is the comparison of overall distance "traveled" between the aggregated storage resources and the conventional resources in this particular set of regulating resources. Figure 6, shows the graphical results between the AGC signals (δ_i) sent to each type of resource and their aggregated response (δ_r) over the space of 24 hrs. The storage graph shows how many more regulation instructions are sent to the storage device and that translates into a longer distance traveled over the same period of time.

Figure 6: AGC signals (blue line) and the resources response to the AGC signal (red line)



6. Additional Recommendations

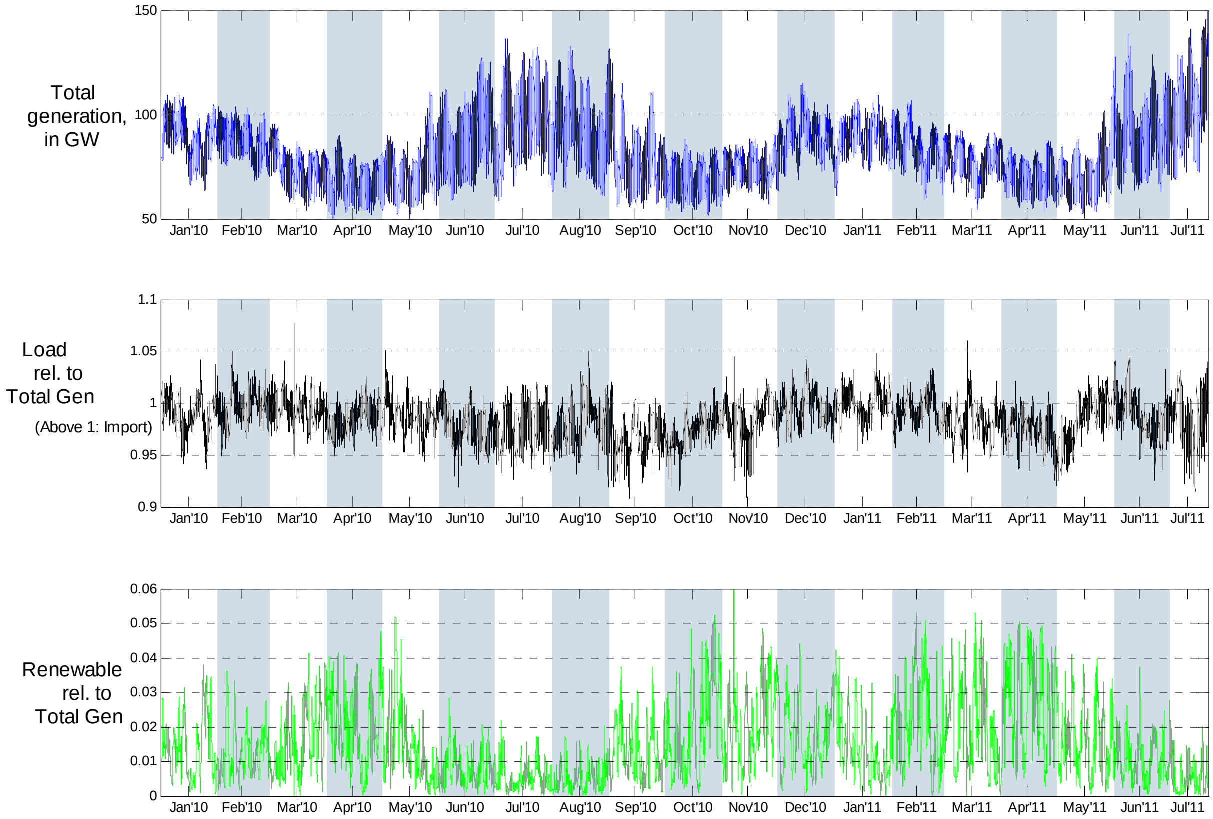
Based on the observed results, KEMA suggests the following:

1) The results for CPS1 and BAAL suggest further investigation of the correlation between the load patterns (both daily and seasonality) and the PJM regulation requirement.

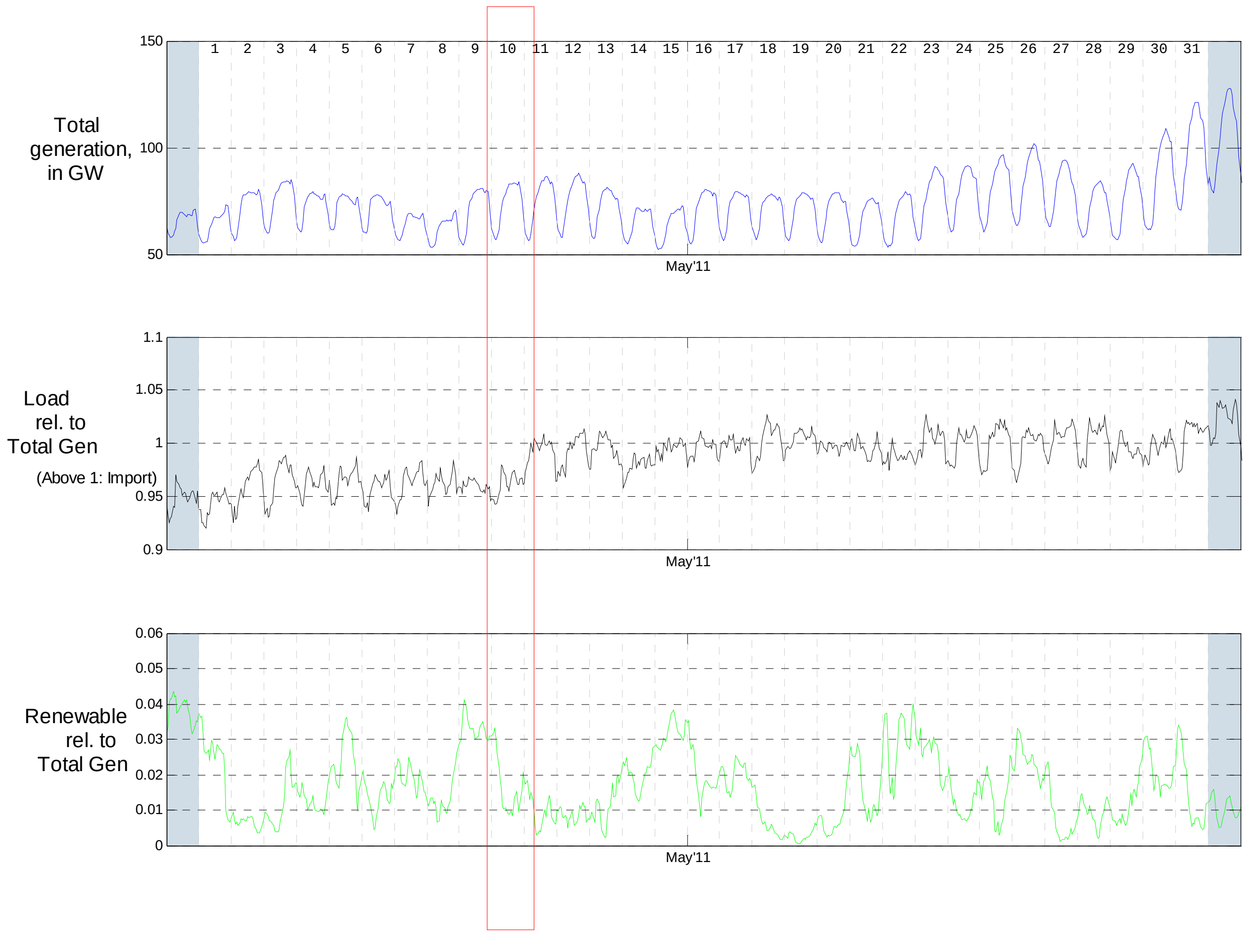
2) Since KEMA merely replicated PJM’s current AGC algorithm in KERMIT and did not attempt to change the RegA and RegD signals to see if any material changes in results might occur, PJM may consider exploring this subject and compare it to the results presented in this report.

A. PJM KERMIT Model Summary

A.1. Generation, Load and Renewable Profiles (system-level) for the Jan'2010 to July'2011.



A.2. An example a day is picked for each month (May 2011 is shown)



B. CPS1 and Other Control Metrics Simulation Results

Full data worksheets for the following simulation results are provided in a separate electronic Excel file (App B Summary of results_v7.4.xlsx).

1) Base Cases – one for each of the 12 selected dates.

- Current PJM Regulation Requirements Cases – for all 12 selected dates and conventional to fast regulation resources scenarios.

- Expanded PJM Regulation Requirements Cases – for all 12 selected dates, conventional to fast regulation resources scenarios and regulation requirements values.

C. MW – Mile Calculation Results

Full data worksheets for the January 21, 2011 date comparing the MW-mile results for the aggregated fast regulation storage against the aggregated conventional plants providing regulation for that date by plant type.

The plant types used were:

- Aggregated Coal Plants
- Aggregated Combined Cycle Plants
- Aggregated Combustion Turbines Plants
- Aggregated Hydro Plants.

The numbers are provided in a separate electronic Excel file (App C MMM_v5_12-08-2011_AT 1SEC.xlsx).

D. AGC BAAL Performance Calculation Results

Full data worksheets for the following simulation results are provided in a separate electronic Excel file (App D BAAL results_V4.3.xlsx).

1) Base Cases – one for each of the 12 selected dates.

- Current PJM Regulation Requirements Cases – for all 12 selected dates and conventional to fast regulation resources scenarios.

- Expanded PJM Regulation Requirements Cases – for all 12 selected dates, conventional to fast regulation resources scenarios and regulation requirements values.

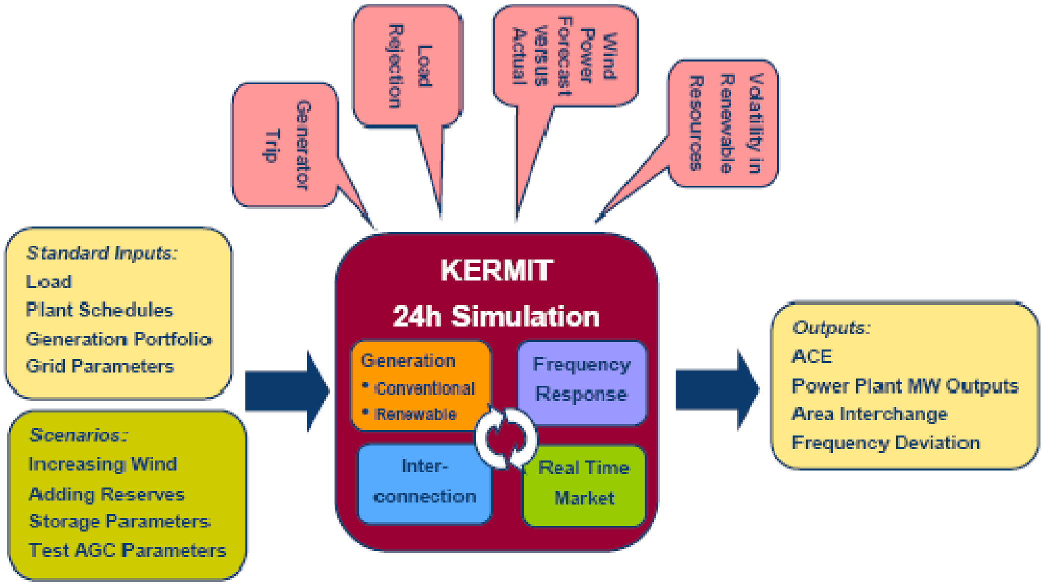
E. KEMA Renewable Model Integrating Technologies (KERMIT)

The KERMIT model is configured for studying power system frequency behavior over a time horizon of 24 hours. As such, it is well suited for analysis of pseudo steady-state conditions associated with Automatic Generation Control (AGC) response including non-fault events such as generator trips, sudden load rejection, and volatile renewable resources (e.g., wind) as well as time domain frequency response following short-time transients due to fault clearing events.

> **KERMIT.** "This is a software product used by KEMA to analyze the bulk power system for integrating renewable energy sources. This is not a commercial software product but an analysis tool for high level study where automatic generation control must be modeled; control area interconnections simulated and generator inertia can be modeled by balancing authority, not nodes. The time span for modeling is generally 1 second to 1 hour, so a 24-hour model simulation can be done in a balancing area for wind, congestion and regulation services in 15 to 30 minutes. Energy storage efficiency and response rates are included in the model."
>
> **Analysis Tools for Sizing and Placement of Energy Storage in Grid Applications - A Literature Review; Pacific Northwest National Lab, September 2010**

KERMIT model inputs include data on power plants, wind production, solar production, daily load, generation schedules, interchange schedules, system inertias and interconnection model, and balancing and regulation participation. Parameters for electricity storage are also inputs – power ratings, energy capacity or "duration" of the storage at raged power, efficiencies, and rate limits on the change of power level. Model outputs include ACE, power plant output, area interchange and frequency deviation, real time dispatch requirements and results, storage power, energy, and saturation, and numerous other dynamic variables. The KERMIT Model Overview graphic (Exhibit 1) depicts the model inputs and outputs graphically.

Exhibit 1: KERMIT Model Overview



EXCEL-based dashboards allow the creation of comparative analyses of multiple simulations across control variables and the generation of time series plots of key dynamic variables with multiple simulation results co-plotted for easy comparison. Pivot table analysis allows the 3-D plotting of key metrics (such as maximum ACE) across multiple simulations and scenarios.

The model has a number of useful features aimed at making it effective for analyzing specific conditions and different scenarios including:

- Spreadsheet based data to represent regional power plants.
- Use of actual interchange schedules and load forecasts from typical customer data.
- Analysis of dynamic performance of the power system, the AGC, the generation plants, storage devices:
  - Power spectral density analysis which allows comparison of hour to multi-hour time series (i.e. ACE, plant actual generation, frequency) by mathematical means
  - Computation of NERC CPS1 and CPS2 performance and statistics or other customer control standards
- Computation of useful statistics such as max over a time period, averages, and so on.

It is possible to make direct comparisons of different cases to highlight the results of changes from one scenario to the next, such as increased wind development, increased use of regulation for the same scenario, impact of varying levels of storage, impact of different control algorithms and tuning, and comparison of completely different strategies such as storage versus increased ancillaries. These are presented statistically and were turned into EXCEL pivot tables, or more typically, combined on MATLAB plots to show time series from different cases on the same plots.

F. Methodology: Setting Up the PJM Model

Each KERMIT simulation spans a 24-hour period, with a time step of less than 1 second. The study involves assembly of data from various PJM databases, which is a time-consuming process. The main steps in setting up a KERMIT model are:

1. Selection of “typical” days to study. These typical days are sometimes referred to as “base cases”. One challenge is selecting the limited set of days is that the conclusion of the study can be made for an entire year. Early in the project, both PJM and KEMA agreed that one day from each month be picked to build a base case. This results in a study with 12 base cases.

2. Build detailed model for each base case. This involves setting the time series for each generation resource, system load and interchanges. In addition, as generation response is an important element, key parameters such as ramp rates for each resource need to be represented with reasonable accuracy.

3. Build PJM-specific operational features. This includes calibrating the system inertia so that the frequency response of the system in the base-case days resembles what was captured by the Pi-Historian. Another important calibration is due to the fact that PJM’s AGC uses RegA and RegD to control traditional and fast resources, respectively.

4. Devise scenarios for the study. For each of the base-case day, KEMA and PJM set up variants of it; each variant involves a different combination of Regulation Requirement and Energy-Storage Penetration. The base case itself is one variant for which the Regulation Requirement is 1% of load and Energy-Storage Penetration is 0.

5. Run the model and post-process the results. Overall, the KERMIT simulator ran 1,500 cases. These cases were processed for particular metrics, tabulated/reported in formats that can provide insights into the impact on PJM frequency regulation as the presence of energy-storage technology increases. The chosen metrics for this study are: CPS1, BAAL, and MW-mile.

F.1 Selection of base cases

A total of twelve (12) days from recent months were chosen as the base cases of the simulation study. They are listed in **Error! Reference source not found.**. Since the study began in August

011, the “most recent” month was July 2011. More details about the selection are given in Appendix A.1.

Table 7: Twelve days selected for the study.

Day #	Year	Month	Day	Characterized by			Comments
				Conventional Gen	Interchange	Renewable/Total-Gen ratio	
1	2010	Aug	15	Low	Import	Low	
2	2010	Sep	7	Low	Import	Med	
3	2010	Oct	28	Low	Import	Hi & Ramp	
4	2010	Nov	23	Low	(neutral)	Hi & Ramp	
5	2010	Dec	13	Low	(neutral)	Med	
6	2011	Jan	21	Med	(neutral)	Low & ramp	
7	2011	Feb	18	Low	(neutral)	Hi	
8	2011	Mar	20	Low	Import	Hi	
9	2011	Apr	11	Low	(neutral)	Hi & ramps	Already picked by PJM
10	2011	May	10	Low	Import	Medium & ramp	
11	2011	Jun	15	Med	Import	Medium & ramp	
12	2011	Jul	10	High	Import	Low	Already picked by PJM

NOTE: Data are downloaded from http://www.pjm.com/markets-and-operations/ops-analysis.aspx

F.2 Modeling load and generation resources for the base cases

After the twelve days were chosen for the base cases, KEMA used the following PJM datasets to build the model. Many such data were specific to the resources and have not been publicly available. The major datasets include:

- Hourly schedules for all generation resources in the PJM footprint.
- Hourly interchange profiles for interchanges with neighboring areas.
- Pi-Historian records for frequency, ACE, etc. for the chosen days. PJM provided two-second resolution.
- Key parameters of generation resources, such as nameplate capacity, fuel type, and ramp rates.

- Disturbance records and resulting system-frequency behavior. (This was needed to calibrate the model so that its frequency behavior closely reflects what has been observed in practice.)

There are approximately 600 conventional power generation resources making up the PJM control-area model. They comprise resources that range in power output capacity from a few MW to more than 1,000 MW. The total installed capacity in the model is about 170,000 MW. Depending on the simulated day, the number of on-line resources ranged from 200 to 400.

F.2.1 Modeling PJM-specific Operational Features in KERMIT

F.2.1.1 Representation of PJM and Neighboring Control Areas

There are 19 control areas defined in the KERMIT model; see Figure 7. This number of control areas reflects the number of interchanges that are being monitored by PJM today. In the KERMIT model, there is a tie-line that joins PJM to each neighboring control area; the difference between the scheduled flows and the "actual" (simulated) flows is part of what drives the KERMIT AGC. The other 18 control areas are connected to each other. Overall, the system topology has 19 nodes and 46 branches.

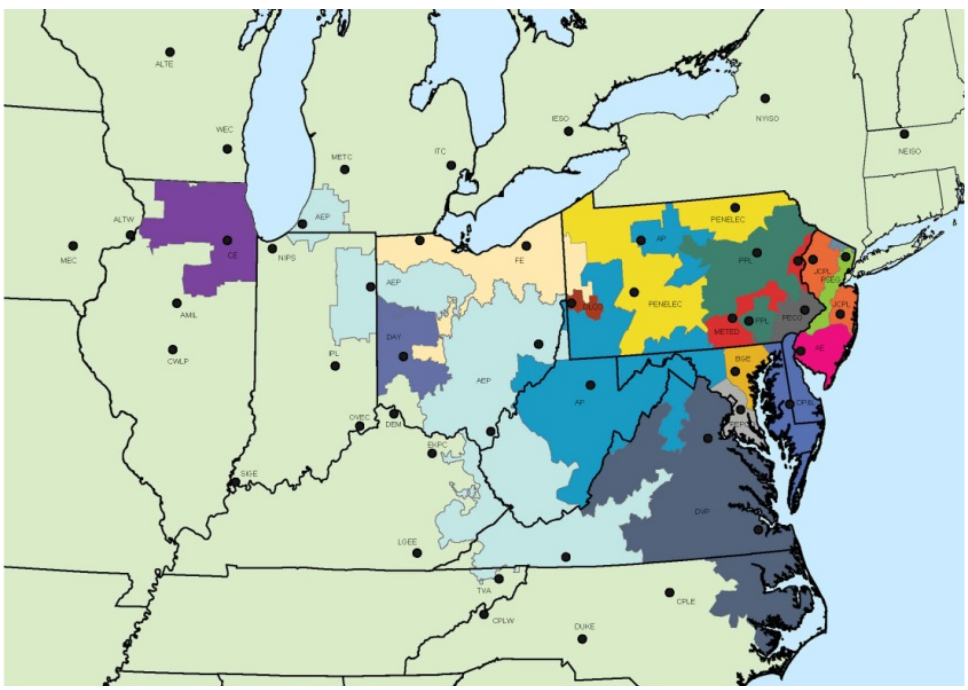


Figure 7: Map showing what the KERMIT model represents.

Green color represents neighboring control areas; non-green areas are sub-areas within PJM. The dots represent the approximate locations of the PSS/E buses chosen for the network-reduction process.

To obtain the topology for the KERMIT model, a network reduction was performed. KEMA started with the PJM provided PSS/E model which is comprised of more than 18,000 buses. From there, the Y matrix for the Eastern Interconnection was built. A number of high-voltage buses (approximate locations indicated as dots in Figure 7) were chosen. A reduced-network Y matrix is calculated by retaining these buses. Since KERMIT represents the entire PJM as a "supernode", all the buses internal to PJM are further merged together (these are the dots in the non-green areas of the map). In the end, a network of 19 buses was created for the study, with connecting impedances sufficient to support the known interchange schedules.

Table 8: The KERMIT model has 19 Control Areas

ID	Control Area	"Installed" Capacity (MW) in model[6]
1	PJM	168,490
2	NYISO	46,977
3	ISO-NE	37,831
4	METC	14,160
5	WEC	10,078
6	ALTE	6,418
7	ALTW	7,829
8	MEC	7,983
9	AMIL	12,776
10	NIPS	5,247
11	IPL	3,514
12	OVEC	2,961
13	DEM	19,018
14	EKPC	3,150

[6] The installed capacity for PJM reflects the reality and is the sum of the nameplate rating of all power plants in PJM. Note that KERMIT represents individual power plants in PJM, but all the neighboring control areas are represented by one equivalent generator. For that reason, it is sufficient in the model to assign sufficient generation for Areas 2-19 to support the transfer over the tie-lines to Area 1 (PJM).

ID	Control Area	"Installed" Capacity (MW) in model[6]
15	LGEE	10,023
16	TVA	43,562
17	CPLW	971
18	DUKE	23,432
19	CPLE	14,121

6.1.1.1 Calibration of KERMIT's system inertia for correct frequency response

Since the frequency response is the central aspect of this study, it is important to correctly represent values/ranges for the system inertia so that the simulated response resembles what PJM has observed in actual operations.

As part of the data-collection process, KEMA requested a list of major disturbances from PJM. Since PJM is a very large system, only a loss of a large generator on the level of 1,000MW or higher would yield a measurable impact on the frequency. Table 9 is the list of major disturbances that PJM provided for this analysis. PJM also provided a detailed record, which contained time series from Pi-Historian for the time period before and after each event. The Pi-Historian data was used to check simulation results against historical data observed in actual operating conditions.

Table 9: Summary of major events on the PJM system in 2010.

The frequency drop due to loss of a major generator provides an indication of the inertia of the entire system at the moment the event occurred.

Start Date & Time	Resource	t_{begin}	t_{end}	f_{begin}	f_{end}	Δ t	Δ f	Δ MW	Ks = (Δf/Δt)/ΔMW
2010-02-18 08:24:32	Loss of Calvert Cliffs #1 & #2 (1691MW)	8:24:32 AM	8:24:38 AM	59.9769	59.9532	6 sec	0.023701 Hz	1,691	2.3E-06
2010-03-13 20:52:25	Loss of Mountaineer #1 (1275MW)	8:52:24 PM	8:52:30 PM	59.9900	59.9418	6 sec	0.048214 Hz	1,275	6.3E-06
2010-03-23 16:12:10	Loss of Rockport #2 (1298MW)	4:12:12 PM	4:12:18 PM	59.9760	59.9257	6 sec	0.050350 Hz	1,298	6.5E-06
2010-05-14 23:01:48	Loss of Susquehanna #1 (883MW)	11:01:44 PM	11:01:52 PM	59.9635	59.9318	8 sec	0.031670 Hz	883	4.5E-06
2010-06-05 14:26:40	Loss of Amos #3 (1256MW)	2:26:42 PM	2:26:48 PM	59.9812	59.9420	6 sec	0.039211 Hz	1,256	5.2E-06
2010-06-23 20:52:20	Loss of Limerick #1 (1103MW)	8:52:24 PM	8:52:30 PM	59.9950	59.9863	6 sec	0.008736 Hz	1,103	1.3E-06
2010-07-07 11:18:24	Loss of Salem #1 (1213MW)	11:18:22 AM	11:18:30 AM	59.9836	59.9481	8 sec	0.035473 Hz	1,213	3.7E-06
2010-07-26 08:37:45	Loss of Rockport #2 (1220MW)	8:37:36 AM	8:37:40 AM	59.9976	59.9643	4 sec	0.033310 Hz	1,220	6.8E-06
2010-08-11 15:08:20	Loss of Gavin #2 (1269MW)	3:08:16 PM	3:08:24 PM	59.9904	59.9558	8 sec	0.034523 Hz	1,269	3.4E-06
2010-08-16 03:06:20	Loss of Braidwood #2 (1199MW)	3:06:20 AM	3:06:24 AM	60.0224	59.9906	4 sec	0.031803 Hz	1,199	6.6E-06
2010-10-15 23:21:05	Loss of Salem #1 (1208MW)	11:20:58 PM	11:21:06 PM	59.9821	59.9363	8 sec	0.045746 Hz	1,208	4.7E-06
2010-10-17 05:12:28	Loss of Salem #2 (1158MW)	5:12:24 AM	5:12:28 AM	59.9844	59.9436	4 sec	0.040833 Hz	1,158	8.8E-06

Even though the disturbance events did not occur on the same dates as those picked for the study, the estimated system inertia for those moments can be used as a guide for setting the values in KERMIT. The range of inertia values derived empirically from the analyzed events is shown in Figure 8 as a scattered plot. The shown parameter **Ks** (the inverse of which, or **1/Ks**, is the system inertia) is dependent on the amount of on-line generation, which is expected. Points on the scattered plot are partitioned into two groups, as enclosed by the green and red shapes. These two shapes serve as upper and lower ranges for the **Ks** value in the KERMIT model.

Each KERMIT simulation case runs over 24 hours, thus the parameter **Ks** is allowed to vary up to 24 times during the simulation. Since each power plant in PJM is represented in the model, the hourly-schedule data, allows one to decide whether the inertia of that plant should be counted toward the system-based value of **Ks**. In that way, one can build a time series for **Ks** that reflect the collection of power plants that are on line during each hour. However, as power plants are not the only elements in the physical system that contributes to system inertia, the time series is then adjusted further so that it is in the ranges that Figure 8 suggests.

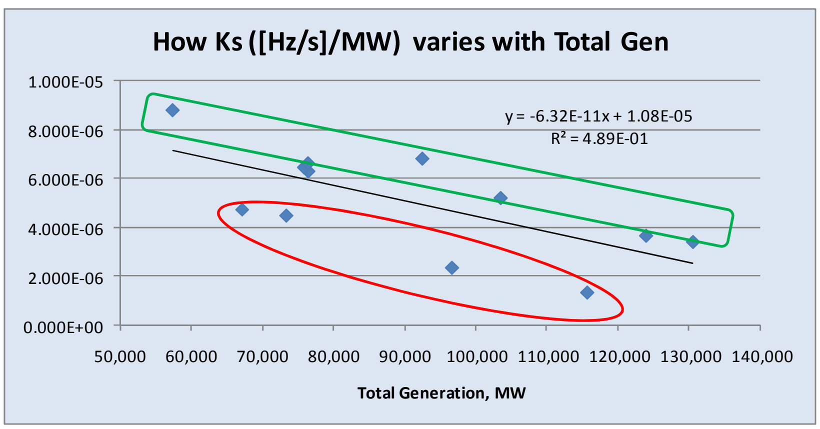


Figure 8: Estimated System Inertia based on empirical data.

The parameter Ks is the inverse of the inertia. The scattered plot reveals that as the system gets "stiffer" (more mass, or smaller Ks) as there is more generation on line.

6.1.1.2 Representation of PJM's AGC

The AGC used by KERMIT is of generic type; that is, it continuously calculates ACE (Area Control Error) from the simulated frequency and interchange deviations and produces a signal called PACE ("Processed ACE"). PACE is then broadcast to the generating units that participate in the regulation.

To mimic PJM's AGC as close as possible, KEMA obtained the specific parameters that PJM uses in their ACE formula and in the associated numerical filters. Furthermore, for PJM, the so-called PACE is actually a set of two signals, RegA and RegD. The processes of producing RegA and RegD both obtain ACE as the input, and involve a PI Controller and various limiters and low-pass filtering. PJM uses RegA on conventional regulation resources and RegD on fast regulation resources. Figure 9 below shows samples of actual RegA and RegD signals over a 24-hour period.

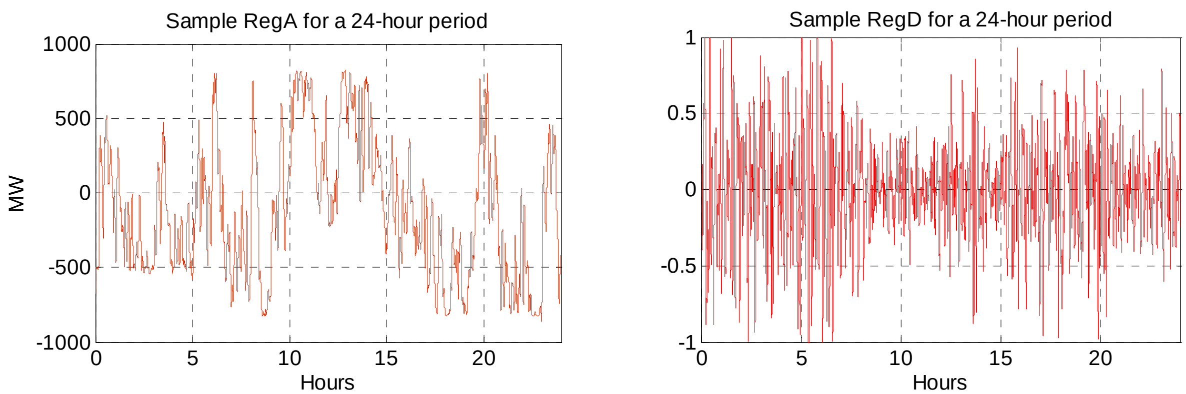


Figure 9: Sample RegA and RegD signals, from PJM's historical data of 2011-04-11.

After the analytical form (block diagrams and formulae) was made available, KEMA implemented the control in Simulink® and validated the modeled RegA and RegD against the actual recording. The results are shown in Figure 10. The Simulink® implementation was able to match RegD perfectly. The match for RegA was very good, but not 100% perfect, due to the fact in the real process, PJM occasionally applies a manual reset to the PI Controller; KEMA and PJM chose not to mimic that process in Simulink® because KERMIT is designed to be an automatic environment and does not accept human intervention when the simulation is in progress.

Once the RegA and RegD processes were validated, the stand-alone block diagram was integrated into KERMIT. In the final model, KERMIT represents the regulation within PJM territory with RegA and RegD, whereas all the external areas (e.g., NYISO, etc.) have generic AGC controls.

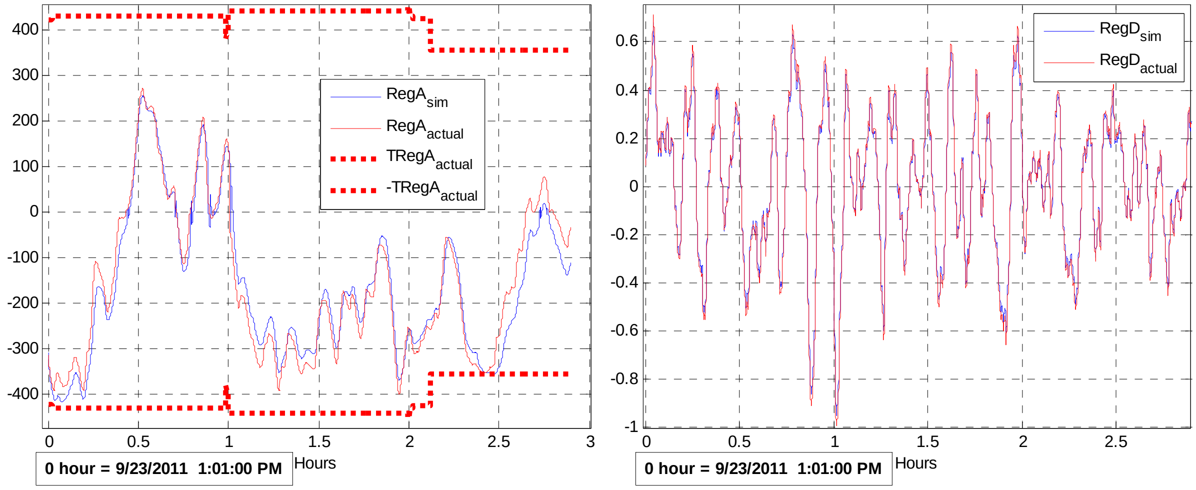


Figure 10: Implementing RegA and RegD calculation processes in Simulink and KERMIT

For validation, the simulated signals (Blue) are compared against actual signals (Red).

G. Study Objectives

KEMA's Renewable Model Integrating Technologies tool and methodology known as KERMIT (see Section 4), was used as the principal study application. PJM set a short list of goals for the study that were used by KEMA to customize the KERMIT methodology and tool for the purpose of the study:

1) Establish a platform for these and other long term dynamics / system regulation and frequency response studies of the PJM system and its resources by developing a KERMIT model implementation of the PJM system and calibrating it to observed real time data

    a) This goal was met by the effort undertaken by KEMA to create a PJM power system model in KERMIT's environment that was calibrated and validated to correctly represent the PJM generation control system dynamics in the real time timeframe. Measures for the correct replication of frequency deviation and ACE performance under significant system events were compared between the KERMIT simulation results and PJM historical records. The summary results of this effort are summarized in Section 5.1.

4) Examine the relative performance and impact on system performance of fast versus traditional regulation resources

    b) This goal was also met and the results detailed in Section 5.2. For this purpose, KEMA and PJM agreed to focus the observations on the simulation results for the Control Performance Standard 1 (CPS1) against both the simulation base case and the PJM historical record. Over a 1,000 different scenarios were run to produce enough comparison data to draw out the findings of this report. The KERMIT simulation results were able to replicate the CPS1 performance for the base case against the PJM historical record. Results of the additional simulation scenarios also provided encouraging results to support the addition of fast regulation resources to specific penetration levels. The simulation also found a predicted point of diminishing returns in CPS1 performance.

5) Simulate and analyze the metric of a "MW mileage" or pay for performance tariff for regulation services that can differentiate between resources with different response rates.

    c) This goal was also achieved and the results presented in Section 5.2.3. KEMA's proposed formulation for the MW-mile measures and the pay for performance metrics were tested for selected representative unit types and classes and the results compared against each other by unit class and type. Since the MW-mile measures and metrics are new, more investigation is suggested into what variables and conditions affect the results the most.

6) Simulate and analyze the PJM "response accuracy" metric and simulate the effectiveness of this metric for different scenarios of unit response and non-response.

   d) For this activity, PJM suggested the testing of NERC's BAAL metric. PJM provided KEMA with an Excel-based template that does the actual BAAL calculations.[7] KEMA consulted the relevant NERC documents, provided by PJM, for how BAAL is defined and calculated, and wrote the Matlab® code for data processing. This Matlab® code was validated using PJM's Excel-based BAAL template as the benchmark. KEMA implemented the Balancing Authority ACE Limits (BAAL) metric in KERMIT and applied the same to the simulation outputs used in for the CPS1 tests. This goal was therefore reached and the results presented in Section 5.2.2.

[7] http://www.nerc.com/docs/standards/sar/BAL-007-011_pre-ballot_clean_05Sep06.pdf