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Review of the Recent Frequency Performance of the Eastern, Western and ERCOT Interconnections

Carlos Martinez, Song Xue, and Martha Martinez

Electric Power Group (EPG) and CERTS

December 2010

The work described in this report was funded by the Federal Energy Regulatory Commission, Office of Electric Reliability through a subcontract administered by the Lawrence Berkeley National Laboratory, which is operated by the University of California for the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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Abstract

The reliable operation of an electric power system depends on careful management of the balance between generation and load to ensure that system frequency is maintained within narrow bounds around a scheduled value. Yet, maintaining frequency at the scheduled value is challenging because the load served is continuously changing, and occasionally, events such as the sudden loss of a large generation plant or large amount of load, cause frequency to deviate abruptly. This report reviews the recent history of frequency performance for all three U.S. interconnections: Eastern, Western, and the Electric Reliability Council of Texas (ERCOT). The review is based on data collected by the North American Electric Reliability Corporation (NERC). The review focuses on frequency response, which measures the performance of the interconnections immediately following sudden, large imbalances between load and generation. Trends in frequency response are presented and preliminary efforts are made to relate frequency response to other aspects of frequency performance and to examine aspects of the methods used to calculate frequency response.

Acknowledgments

The work described in this report was funded by the Federal Energy Regulatory Commission, Office of Electric Reliability through a subcontract issued by the Lawrence Berkeley National Laboratory, which is operated by the University of California for the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

The Principal Investigator for the overall project is Joseph H. Eto, Lawrence Berkeley National Laboratory.

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The study authors, alone, however, bear sole responsibility for technical adequacy of the analysis methods and the accuracy of the study results.

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Acronyms and Abbreviations

ACE	Area control error
AGC	Automatic generation control
CERTS	Consortium for Electric Reliability Solutions
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
FMA	Frequency Monitoring Application
Hz	Hertz
LCL	Lower control limit
mHz	Milli-hertz
MW	Megawatt
NERC	North American Electric Reliability Corporation
RAA	Resources Adequacy Application
RMS	Root mean squared
RS	Resources Subcommittee
UCL	Upper control limit

Executive Summary

The balance between load and generation within an interconnected electricity system is directly reflected in the frequency of an interconnection. Within North America, the scheduled value for frequency is normally 60 cycles per second or Hertz (Hz). Maintaining frequency at the scheduled value is challenging because the load served is continuously changing, and occasionally events, such as the sudden loss of a large generation plant or a large amount of load, cause frequency to deviate abruptly.

System operators strive to maintain frequency at the scheduled value through a variety of automatic (both autonomously and centrally controlled) and manual actions that are carried out by generation resources and sometimes by demand resources. Thus, deviations in frequency from the scheduled value are a measure of the capabilities of the resources as well as the efficacy of system operators' efforts to deploy them to provide these actions in anticipation of and in response to these challenges.

This report reviews the recent history of frequency performance for all three U.S. interconnections: Eastern, Western, and the Electric Reliability Council of Texas (ERCOT). The review focuses on frequency response, which measures the performance of the interconnections immediately following sudden, large imbalances between load and generation. Trends in frequency response are presented and preliminary efforts are made to relate frequency response to other aspects of frequency performance and to examine aspects of the methods used to calculate frequency response.

The review is based on data collected by the North American Electric Reliability Corporation (NERC).

Frequency Response of the Interconnections over Time

Frequency response is a measure of the collective ability of the synchronized generation and load in an interconnection to arrest and then stabilize rapid changes in frequency. It is measured by relating a change in the balance between load and generation (expressed in units of megawatts or MW) to the associated change to the settling frequency (expressed in units of 0.1 Hz).[1]

Traditionally, frequency response studies have focused on measuring performance following discrete events involving the sudden loss of a large amount of generation or load. The methods used to calculate frequency response have evolved over time. This evolution has been aided by improvements in monitoring technology, which enable more precise measurement of frequency before and after an event. Still, the methods reflect limitations imposed by the absence of consistent data on the magnitude of the initiating net change between load and generation as well as ongoing improvements in methods used to measure the change in frequency resulting from an

[1] For stable interconnection operation, the frequency response must have a *negative* value, which indicates that there has been a net increase in generation output for a decrease in frequency (or vice versa). By convention, however, industry discusses frequency response as a *positive* value.

event. Today, there remain differences of opinion within the industry regarding the best means of achieving compliance for calculating frequency response identified in the NERC standard.[2] There are specific guidelines for calculating frequency response from the NERC Resources Subcommittee.

For this study, we applied a consistent method widely used today within the industry, based on the aforementioned guidelines from the NERC Resources Subcommittee, and used the best available data to calculate trends in the frequency response of all three U.S. interconnections over time. The method first identifies frequency response events involving the loss of generation consistently based on the size of the frequency excursion.[3] It then estimates the amount of generation lost (because the actual amount of generation lost is not readily or consistently available) by finding the balancing authority with the greatest change in area control error (ACE) and adjusting this value to eliminate the effect of frequency bias component of ACE. Finally, it estimates the change in frequency using frequency averages measured over pre-defined time windows before and after the event. For the long-term assessment of trends in frequency response from 2002 to 2008, the method uses 1-minute averages of frequency and ACE.

Figure ES- 1 presents annual trends and variability in interconnections frequency response from 2002 to 2008. We find that the median frequency response of both the Eastern and Western Interconnections has declined by about one-fourth during this period, while the total load served has increased by approximately 10%.[4] This finding is consistent with past investigations of frequency response. To these earlier findings, we have added more recent data that reconfirms and further extends trends identified previously. In addition, for the first time, we show the variability in frequency response within the year that surrounds these trends. Of note, presentation of the distribution indicates the extent to which frequency response varies, sometimes considerably, from the median value.

Frequency Deviations at Different Hours of the Day and Within the Hour

Frequency deviation is defined as the difference between actual and scheduled frequency. We examined the magnitude and timing of these deviations by calculating the Root Mean Square (RMS) of these deviations for 2007 and 2008 using 1-second frequency data for weekdays, only.[5] We established interconnection-specific RMS thresholds in order to focus on the largest frequency deviations. The thresholds are based on statistical concepts from process control. We developed visual presentations of the largest RMS of frequency deviation as a function of time of day each month, as well as a function of time within the hour including 5-minute time periods within the hour.

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[2] See BAL-003-0, Frequency Response and Bias, Requirement R2.1.

[3] This study does not examine frequency response associated with events involving the loss of load.

[4] NERC Long Term Reliability Assessment at http://www.nerc.com/page.php?cid=4|61.

[5] 1-second data from improved monitoring technologies were only available for the years 2007 and 2008.

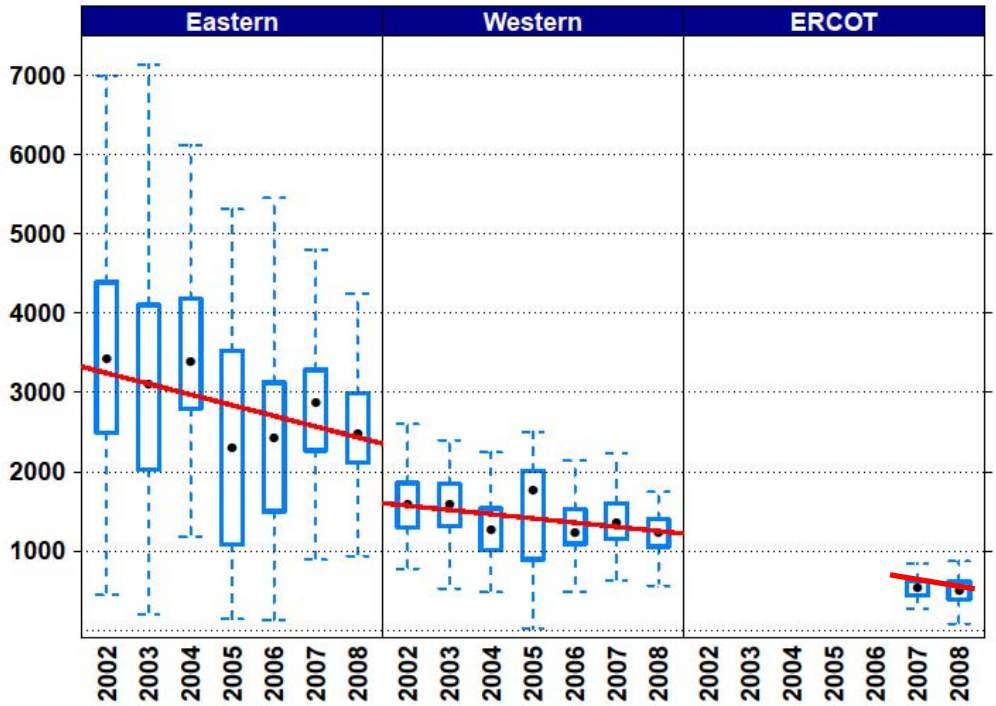

Figure ES- 1. Yearly Trends in the Frequency Response of the Eastern, Western and ERCOT Interconnections

Figure ES- 2 and Figure ES- 3 present the findings for the Eastern Interconnection. They confirm anecdotal observations well-known within the industry that, on weekdays, there are predictable months during a year and predictable times during the day (i.e., during the early morning and late evening) as well as 5-minute time periods within an hour (i.e., just before and after the top of the hour) when the RMS of frequency deviation is consistently larger than it is at other times of the day or within the hour. These periods coincide with times when load is changing rapidly and system operators are ramping in and out large blocks of power within the interconnection to execute market arrangements.

A systematically larger RMS of frequency deviation at predictable times of the day or minutes of the hour indicates that the frequency control reserves deployed at these times do not manage the imbalances between generation and load that occur at these times as closely as they do at other times. There is a concern that, as a result, these may be times when the fast, primary frequency control reserves, which are held to respond to sudden, large imbalances between load and generation, are being deployed and could be depleted.[6] Hence, we undertook a preliminary examination to explore whether times of low frequency response were correlated with times of large RMS of frequency deviations. Our examination was inconclusive statistically, in part due

[6] Undrill, J.M. 2010. Power and Frequency Control as it Relates to Wind-Powered Generation. LBNL-4143E. Berkeley: Lawrence Berkeley National Laboratory.

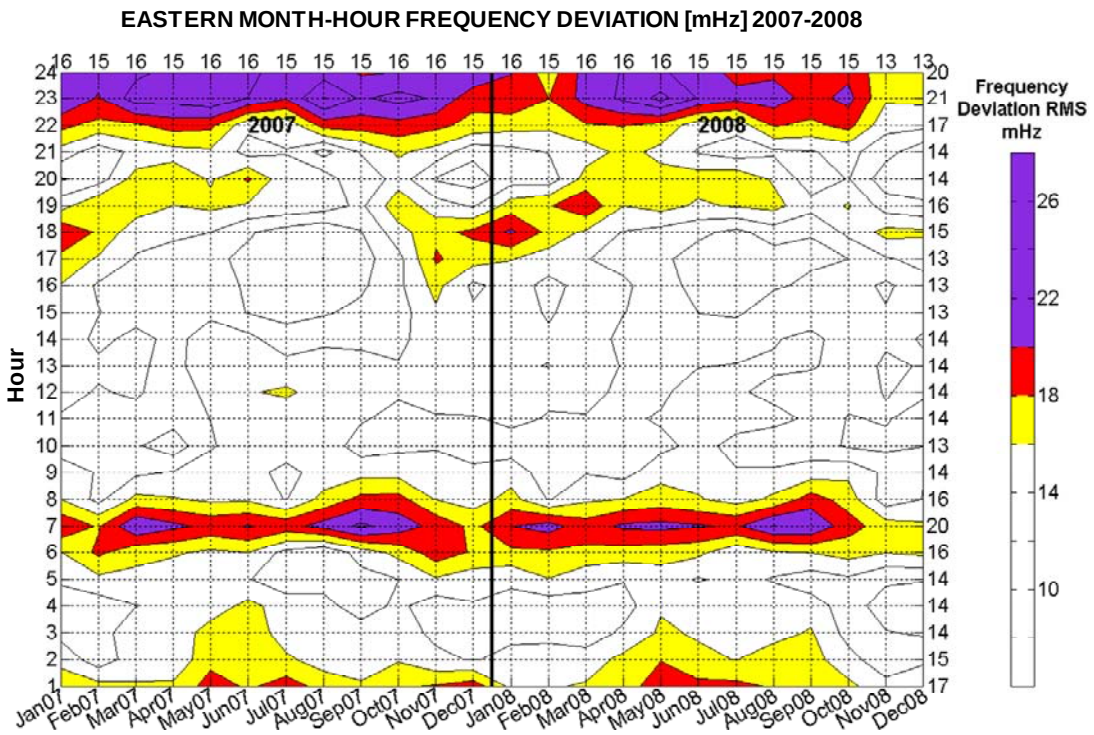

Figure ES- 2. Eastern Interconnection RMS of Frequency Deviation by Month and Hour of the Day - 2007-2008

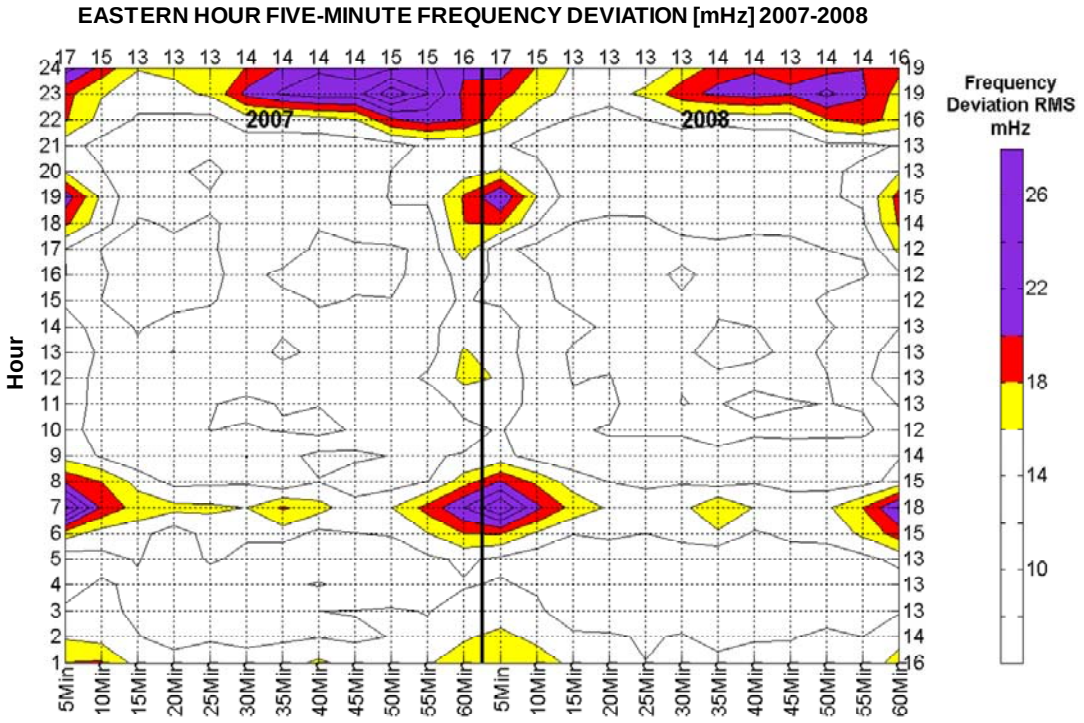

Figure ES- 3. Eastern Interconnection RMS of Frequency Deviation Hour and Five-Minute Period within the Hour - 2007-2008

to the comparatively small number of frequency response events that occurred within any given year, and the even smaller number of these events that occur at times when we observed larger RMS of frequency deviations. Still, we believe this to be an important area for future investigation.

A Preliminary Examination of Aspects of Current and Evolving Methods for Calculating Frequency Response

The methods used to calculate frequency response continue to evolve as new sources of frequency data become available and different approaches are considered for measuring the elements. Preliminary examinations of three aspects of current and evolving methods for calculating frequency response were conducted.

The first compared the frequency responses for 2007 and 2008 to the sum of frequency bias settings reported by balancing authorities within each interconnection. The comparison confirmed the appropriateness of the interconnection frequency bias adjustment factors, which were used to estimate the MW imbalance term in the frequency response calculations.

The second compared the frequency responses for 2007 and 2008 and calculated 1-minute averages of frequency and 1-second averages of frequency now available from advanced monitoring technologies. Methods for calculating frequency response based on 1-second averages of frequency are in an initial state of development and this comparison contributes to the evolution of these methods.

The third presented a newly developed method for estimating the frequency sensitivity of each interconnection during low frequency events. More research is recommended to refine the data and analysis methods to increase understanding of frequency sensitivity trends and their implications for reliability.

Concluding Remarks

Applying consistent methods and data, we confirm and extend industry reports that frequency response has been declining within the Eastern and Western Interconnections. We also provide for the first time information on the statistical distribution of frequency response associated with these trends. We document anecdotal observations that, on weekdays, large RMS values of frequency deviations take place at predictable periods during the day and within the hour. We did not find a statistically significant relationship between the times of larger RMS of frequency deviation and times of lower frequency response, but recommend this topic for future investigation. We also conducted preliminary investigations of selected, emerging topics on the measurement of frequency response.

1. Introduction

The balance between load and generation within an interconnected electricity system is directly reflected in the frequency of an interconnection. Within North America, the scheduled value for frequency is normally 60 cycles per second or Hertz (Hz). Maintaining frequency at the scheduled value is challenging because the load served is continuously changing, and occasionally, events such as the sudden loss of a large generation plant or a large amount of load, causes frequency to deviate abruptly.

System operators strive to maintain frequency at the scheduled value through a variety of automatic (both autonomously and centrally controlled) and manual actions that are carried out by generation resources and sometimes by demand resources. Thus, deviations in frequency from the scheduled value are a measure of the capabilities of these resources as well as the efficacy of system operators' efforts to deploy them to provide these actions in anticipation of and in response to these challenges.

This report reviews the recent history of frequency performance for all three U.S. interconnections: Eastern, Western, and the Electric Reliability Council of Texas (ERCOT). The review focuses on frequency response, which measures the performance of the interconnections immediately following sudden, large imbalances between load and generation. Trends in frequency response are presented and preliminary efforts are made to relate frequency response to other aspects of frequency performance.

The review is based on data collected by the North American Electric Reliability Corporation (NERC).

This report is organized in five sections following this introduction:

- In Section 2, we define the metrics used to assess frequency performance and describe the methods and data used to calculate these metrics for the three interconnections.
- In Section 3, we present our findings on the long-term trends in the frequency response of the three interconnections based on a consistent set of 1-minute data for the years 2002 through 2008.
- In Section 4, we present sub-annual patterns in frequency response based on a consistent set of 1-second frequency data for the years 2007 and 2008 that is now available from improved monitoring technologies.
- In Section 5, we present sub-annual patterns in the RMS of frequency deviations also based on 1-second frequency data for the years 2007 and 2008. We focus on identifying trends that occur during predictable times within the year. We also present the results of our preliminary efforts to correlate the patterns of RMS of frequency deviations to the frequency responses reported in section 4.
- In Section 6, we present preliminary findings on selected aspects of the methods and data that are currently and will in the future be used to analyze frequency response.
- In Section 7, a summary of findings and conclusions is presented.

2. Frequency Performance Metrics – Definitions, Methods, and Data

This report relies on two performance metrics to assess aspects of each interconnection's performance in maintaining frequency at scheduled values. The first, called frequency response, measures, among other things, the performance of the interconnections following sudden, large imbalances between load and generation, such as events involving the loss of a large generating unit. The second, called RMS of frequency deviation, measures the performance of the interconnections over continuous periods of time. We also examine how the frequency bias settings established annually by the balancing authorities within each interconnection are related to frequency response. Finally, we measure the sensitivity of the interconnection frequency to changes in net ACE during low frequency events. The subsections below formally define each of these measures or aspects of frequency performance and describe the methods and data we used to calculate them and to conduct our assessments.

2.1 Frequency Response

Frequency response is a measure of the collective ability of the synchronized generation and load in an interconnection to arrest and then stabilize rapid changes in frequency. It is measured by relating the change in the balance between load and generation, called MW imbalance (expressed in units of megawatts or MW), to the associated change to settling frequency, called delta frequency (expressed in units of 0.1 Hz), as follows: [7]

$$Frequency\ Response = -\frac{MWimbalance}{10 \times \Delta Frequency}$$

For this report, the Frequency Response definition has been modified by the addition of a negative sign. This allows the presentation of the data as positive values. For stable operation, frequency response must be a negative value, which indicates that there has been a net increase in generation output in response to a decrease in frequency (and vice versa).

Traditionally, the methods used to calculate frequency response have focused on measuring performance following discrete events involving the sudden loss of a large amount of generation or load. The methods used to calculate frequency response have and continue to evolve over time. This evolution has been aided by improvements in monitoring technology sampling rate, which enable more precise frequency measurements of the nadir as well as the initial and settling frequency after a sudden imbalance between load and generation. Still, the methods reflect limitations imposed by the absence of consistent data on the magnitude of the initiating net change between load and generation as well as ongoing improvements in methods used to measure the change in frequency resulting from these events. Today, there remain differences of opinion within the industry regarding the best means of achieving compliance for calculating frequency response identified in the NERC standard.[8] There are currently no NERC standards

[7] Technically speaking, for a stable power system, frequency response must be a negative number. By convention, however, industry describes frequency response as a positive number. This distinction is of fundamental importance and should be borne in mind when discussing related concepts.

[8] See BAL-003-0, Frequency Response and Bias, Requirement R2.1.

for calculating frequency response, although there are guidelines for calculating frequency response from the NERC Resources Subcommittee.

This study focuses on frequency response events involving the sudden loss of generation. These events occur with more frequency than those involving the sudden loss of load. However, no judgment is made or intended to suggest that the sudden loss of generation is more or less important for reliability than the sudden loss of load.

For this study, we used the best available data to date and applied a consistent method proposed and discussed with the NERC Resources Subcommittee and currently in use by NERC reliability monitoring applications to calculate trends in the frequency response of all three U.S. interconnections over time.[9] For the assessment of long-term trends in frequency response presented in Section 3, we used 1-minute averages of SCADA frequency and ACE for 2002 through 2008 taken from the NERC Resource Adequacy Application (Electric Power Group 2002).[10] For the assessment of sub-annual patterns of frequency response presented in Section 4, we used 1-second averages of frequency for the years 2007-2008 taken from the NERC Frequency Monitoring and Analysis Application (Electric Power Group 2002)[11] and 1-minute averages of ACE taken from the NERC Resource Adequacy Application.

Three steps are involved in calculating frequency response using these data: 1) Identification of the events for which frequency response is calculated; 2) Estimation of the MW imbalance (because the actual amount of generation lost is not readily or consistently available); and 3) Estimation of the change in frequency. The methods used for steps 1 and 3 vary depending on whether 1-minute averages of frequency or 1-second averages of frequency are used.

We identified frequency response events by examining times when interconnection frequency changed abruptly. When SCADA 1-minute averages of frequency are used (for long-term assessment presented in Section 3), the difference between two adjacent 1-minute averages of 36 mHz or more is used to identify an event. When 1-second averages of frequency are used (for the sub-annual patterns presented in Section 4), the magnitude of the standard deviation associated with eight consecutive frequency averages is used to identify an event. The standard deviation is first calculated for a rolling set of eight consecutive 1-second averages of frequency and is then compared to an interconnection-specific threshold value. Whenever the standard deviation exceeds a threshold, the deviation is classified as a frequency response event. The thresholds identified for the Eastern, Western and ERCOT Interconnections are 6, 9, and 40 mHz, respectively.

We estimated the MW imbalance for each identified event using 1-minute averages of ACE. The balancing authority reporting the greatest change in ACE at the time of the event is assumed

[9] NERC. 2006. Directed Research for Frequency Response Historical Analysis, Proposed Standard Validation and Metrics Definition and Validation - Draft: 090306, Attachment A.

[10] CERTS Area Control Error (ACE)-Frequency Real-Time Monitoring System. Electric Power Group. October 2002. http://certs.lbl.gov/certs-rt-pubs.html

[11] NERC Frequency Monitoring and Analysis (FMA) Application: Functional Specifications. CERTS - Electric Power Group. December 2008. http://certs.lbl.gov/certs-rt-pubs.html.

to be the balancing authority that contains the imbalance.[12] The MW imbalance is estimated by removing the frequency bias term from the simple difference in ACE values.[13] The frequency bias term is removed from the ACE equation by subtracting an interconnection frequency bias adjustment factor multiplied by the balancing authority's frequency bias multiplied by the change in frequency. The interconnection bias adjustment factors for the Eastern, Western, and ERCOT Interconnections are 0.6, 0.6, and 0.1, respectively.[14]

As an illustration, for imbalance events in the Eastern Interconnection, the MW imbalance is calculated as follows:

$$\begin{aligned} MWimbalance &= \max(\Delta \text{balancing authority ACE}) - \\ &\quad [0.6 \times 10 \times (-\text{balancing authority frequency bias}) \times \Delta \text{frequency}] \end{aligned}$$

We estimated the change in frequency for each event using averages of frequency. When 1-minute averages of frequency are used, the change in frequency is simply the same difference in averages used to identify the event. When 1-second averages of frequency are used, the change in frequency is the difference between two averages of frequency calculated over two different time periods. For the initial frequency (i.e., the frequency immediately prior to the event), the averaging period is the 15 seconds prior to the event. For the settling frequency (i.e., the frequency at which frequency settles temporarily following the event), the averaging period is 32 seconds, starting 20 seconds after the event.[15]

[12] This method does not provide a reliable estimate of the total imbalance when the frequency event is caused by a loss of generation from a generating unit that is jointly owned and the output from that unit is spread among more than one balancing authority. The method is also not reliable, if the balancing authority containing the imbalance event did not provide ACE data to the NERC monitoring system. Research is in progress to improve the reliability of methods for calculating MW imbalance.

[13] It should also be noted that this method for estimating MW lost is biased because it eliminates the contribution of the balancing authority, itself, in responding to the imbalance. The extent of this bias must be established through more detailed investigation of each event.

[14] Section 6 of this report compares the observed frequency response of each interconnection to the sum of the frequency bias settings established by the balancing authorities within the interconnection. This comparison confirms the appropriateness of the interconnection bias adjustment factors used to calculate MW imbalance in this section.

[15] Section 6.2 presents a comparison of median annual frequency response calculated with both 1-minute and 1-second averages of frequency.

An Alternate Calculation of Frequency Response

The NERC Resources Subcommittee (RS) estimates interconnection frequency response performance annually using data on large frequency deviations collected and prepared by volunteers from the balancing authorities. There are often no measurements of the generation or load lost during these events, and the procedures for estimating the change in frequency are not uniform. This report applies the proposed method presented and discussed with NERC Resources Subcommittee that consistently uses Balancing Authorities' ACE to estimate the MW imbalance and the change in frequency as defined by the Frequency Response Standard Drafting Team (FRSDT) for all events recorded between 2002 and 2008.

We obtained data from FERC staff for four generation loss events within the Eastern Interconnection that allowed us to calculate frequency response. This calculation is based on a direct interpretation of the frequency response definition for comparison to the method used in this report, which involved estimating the MW imbalance and change in frequency from more aggregated information (such as ACE and 1-minute averages of frequency). FERC staff provided information on the exact amount of generation lost during each event from various sources and also a direct measurement of the settling frequency (point B) using the NERC Frequency Monitoring Application developed by DOE. The results of the two methods for calculating frequency response are presented below.

Comparison of Frequency Response Calculated Using Two Methods

Using FERC Data					Using NERC Data							
Events FERC Data Date and Time	FERC Frequency (Hz)	FERC Freq. Delta Change Estimated: (60-FERCFreq) (Hz)	FERC MW Loss	Frequency Response Estimated (MW/0.1Hz)	Corresponding NERC Data Events Date and Time	Frequency Bias of BA with Highest ACE (MW/0.1Hz)	Highest Delta ACE for BA with Highest ACE (MW)	Frequency Point A	Frequency Point B	Frequency Delta Change Calculated (Hz)	MW Loss Estimated (MW)	Frequency Response Estimated (MW/0.1Hz)
3/26/2009 4:51	59.920	0.080	2338	**-2923**	3/26/2009 4:53	319	2442	60.005	59.931	0.074	2584	**-3489**
4/6/2009 6:00	59.941	0.059	600	**-1017**	4/6/2009 6:02	1344	363	NA	NA	0.025	565	**-2258**
7/6/2009 14:37	59.930	0.070	1702	**-2431**	7/6/2009 14:39	465	161	60.005	59.945	0.061	330	**-544**
9/12/2009 13:30	59.928	0.072	1200	**-1667**	9/12/2009 13:33	1106	337	NA	NA	0.019	466	**-2401**

We find that the estimates of frequency response developed using the FERC data are closer to zero than the estimates developed using the methods used in this report for 3 of the 4 events analyzed. A review of the third event confirms that portions of the lost generation output were accounted for by multiple balancing authorities, which is a known shortcoming of the current NERC method (see footnote 11). The differences in frequency response estimated using the two methods are significant. No two estimates differ by less than 30%; one is twice as large as the other, while one is four times larger than the other.

It is difficult to draw definitive conclusions from this limited comparison of methods due to both the small number of events analyzed. We recommend improved frequency data collection, direct measurement of the loss of generation, archiving and investigation of alternative processes for identifying abnormal frequency events and calculating frequency response.

2.2 RMS of Frequency Deviation

Frequency deviation is defined as the difference between actual and scheduled frequency. We examined the magnitude and timing of these deviations by calculating the Root Mean Square (RMS) of these deviations, as follows:

$$(Frequency\ Deviation)_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} FreqDev^2} = \sqrt{\frac{FreqDev_1^{\ 2} + FreqDev_2^{\ 2} + ...FreqDev_n^{\ 2}}{n}}$$

Where

$FreqDev = Frequency\ Actual - Frequency\ Scheduled$

$n = the\ number\ of\ frequency\ deviation\ values\ in\ the\ period$

Data on the actual and scheduled frequency for each interconnection for 2007 and 2008 are taken from NERC Frequency Monitoring Application (Electric Power Group 2002).[16] The application takes explicit account of time error corrections. For this study, the RMS of frequency deviation is calculated only for weekdays.

We developed thresholds to distinguish between larger and smaller RMS of frequency deviations using statistical concepts from process control. Figure 1 presents hourly means and standard deviations of the RMS of frequency deviation for the Eastern Interconnection 2008.

The charts indicate that any hour with a mean RMS of frequency deviation greater than 19 mHz and corresponding to a standard deviation of RMS of frequency deviation greater than 4 mHz exceeds what process control theory labels as an upper control limit. These limits (both upper and lower) are set at three standard deviations above and below the mean.

Figure 1 shows that in 2008 during hours 7 and 23 the Eastern Interconnection mean RMS of frequency deviation was at or above the upper control limit of 19 mHz, and the RMS standard deviation was above the upper control limit of 4 mHz during hours 7, 18, 20, and 23.[17]

We applied this approach to the RMS of frequency deviations observed for each interconnection. We further added a 20% margin to the upper control limits identified through this process in order to focus on the very largest RMS of frequency deviations. Thus, the thresholds for RMS of frequency deviations used in this study are 22, 27, and 36 mHz for the Eastern, Western, and ERCOT Interconnections, respectively.

[16] 1-second data from improved monitoring technologies were only available for the years 2007 and 2008.

[17] The current threshold in the NERC standard for the Eastern yearly Epsilon is 18 mHz. See http://www.nerc.com/filez/eplimits.html

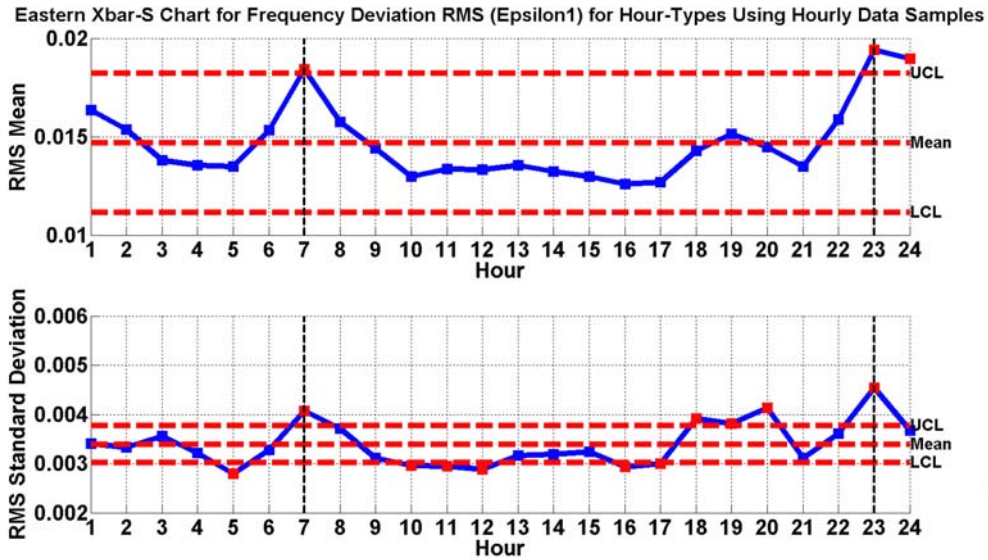

Figure 1. Eastern Interconnection RMS of Frequency Deviation for 2008 by Hour of the Weekday

2.3 Frequency Bias

Frequency bias[18] is an approximation of the frequency response that is set annually by balancing authorities to use in their Area Control Error (ACE) control equation, which in turn guides the operation of automatic generation controls. It is not a frequency performance metric, but it is used to calculate the metrics identified in the NERC Reliability Standards.[19] Frequency response is an observation or measurement of the performance of an interconnection (or balancing authority) following an identified frequency event. Frequency bias is the average of the observations or measurements for certain generation losses during on-peak hours that is established yearly by balancing authorities following NERC reliability rules.[20]

NERC standards have a requirement that "each balancing authority shall establish and maintain a frequency bias setting that is as close as practical to, or greater than, the balancing authority's frequency response."[21] There is another requirement that the balancing authority "shall have a monthly average frequency bias setting that is at least 1% of its estimated maximum generation."[22] Each balancing authority within an interconnection then reports its frequency bias setting annually to the NERC Resources Subcommittee. After review and modification by the NERC Resources Subcommittee, the bias settings are posted on the NERC website.

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[18] The NERC Glossary definition is "[a] value, usually expressed in megawatts per 0.1 Hertz (MW/0.1 Hz), associated with a Balancing Authority Area that approximates the Balancing Authority Area's response to interconnection frequency error."

[19] See BAL-001-0, Real Power Balancing Control Performance.

[20] See BAL-003-0, Frequency Response and Bias, Requirement R2.1.

[21] NERC Standard BAL-003, requirement 2. Referring to footnote 4, this means that frequency bias would be equal to or a larger positive number than frequency response when, following current industry conventions, frequency response is expressed as a positive number.

[22] NERC Standard BAL-003, requirement 3.

We summed the frequency bias settings reported by each balancing authority within an interconnection and compared this sum to the median of the interconnection's frequency responses recorded during the year. This comparison allows us to see how adherence to NERC's rules for setting frequency bias averages out over the entire interconnection. The comparison also provides the basis for the interconnection-wide bias adjustment factors described earlier in this section that are used to estimate the amount of generation lost for use in the frequency response calculation. The comparison is presented in Section 6.1.

2.4 Frequency Sensitivity to Net ACE During Low Frequency Events

We developed an empirically-based estimate of the sensitivity of interconnection frequency to changes in net ACE during low frequency events. Low frequency events are identified as times when the frequency of an interconnection falls below a threshold value. The thresholds are -36 mHz, -36 mHz, and -70 mHz for the Eastern, Western, and ERCOT Interconnections, respectively. We then compared the change in frequency to the change in the net ACE of the interconnection at the time of each event. The slope of the linear correlation between these two values provides an empirically-based estimate of the sensitivity of interconnection frequency to changes in interconnection net ACE.

Consistent with the exploratory nature of this examination, two linear correlations were calculated. The first is guided solely by the observations, so both a best fitting slope and intercept is estimated. The second fixes the intercept at zero and then determines the best fitting slope.

The Net ACE and frequency of the interconnections for 2002-2008 is taken from the NERC Resource Adequacy Application (Electric Power Group 2002).[23] It is reported in one-minute intervals.

Data were available to develop these estimates for 2002-2008 for the Eastern and Western Interconnections but only for 2006-2008 for ERCOT. Separate estimates were calculated for on-peak and off-peak hours. The definition of on-peak is hours ending 7-22 Central for the Eastern Interconnection, hours ending 7-22 Pacific for the Western Interconnection, and hours ending 8-22 Central for the ERCOT Interconnection.

The results are presented in Section 6.3.

[23] CERTS Area Control Error (ACE)-Frequency Real-Time Monitoring System. Electric Power Group. October 2002. http://certs.lbl.gov/certs-rt-pubs.html

2.5 Summary of Data Used to Calculate Frequency Performance Metrics

Table 1 summarizes the data used to calculate each of the metrics used in this report.

Table 1. Data Used to Calculate Frequency Performance Metrics

Metric	Input	Years	Time Resolution	Source
Frequency Response	MaxACE	2002-2008	1 minute	RAA
Long-term Trends in Frequency Response	Frequency	2002-2008	1 minute	RAA
Sub-Annual Patterns of Frequency Response	Frequency	2007-2008	1 second	FMA
RMS of Frequency Deviation	Frequency	2007-2008	1 second	FMA
Frequency Sensitivity During Low Frequency Events	NetACE	2002-2008	1 minute	RAA

RAA – NERC Resources Adequacy Application
FMA – NERC Frequency Monitoring Application

3. Long-Term Trends in Interconnection Frequency Response Based on 1-Minute Averages of Frequency

Frequency response is, among other things, a measure of the collective ability of an interconnection to arrest and then stabilize rapid changes in frequency. It is measured by relating the change in the balance between load and generation (expressed in units of megawatts or MW) to the associated change to settling frequency (expressed in units of 0.1 Hz).

As discussed in section 2, the methods used to calculate frequency response have evolved over time. For this study, we applied a consistent method widely used today within the industry, based on guidelines from the NERC Resources Subcommittee, and a consistent data set of the best available 1-minute data to calculate trends in the frequency response of all three U.S. interconnections over time.

Figure 2 shows the frequency response of the Eastern and Western Interconnections from 2002 to 2008 and the ERCOT Interconnections for 2007 and 2008.[24] The median value is shown as a dot. The "box" containing the median defines the upper and lower limits of the inter-quartile range, which bound 50 percent of observed values. The "whiskers" that surround the box bounds values that are within one and one-half times the inter-quartile range above and below the box. Individual outliers that exceed this range, if there were any, would be shown above and below the whiskers. This form of presentation and the definitions of the graphic symbols used to describe the distributions of observations are consistent throughout this report. Table 1 presents the median values and number of observations contributing to them for each interconnection, for each year of data.

We find that the median frequency response of both the Eastern and Western Interconnections has declined by about one-fourth during this period while the total load served has increased by 10%.[25] This finding is consistent with past investigations of frequency response. To these earlier findings, we have added more recent data, which reconfirms and further extends trends identified previously.

In addition and for the first time, we also show the variability in frequency response that surrounds these trends. Of note, the distributions indicate that sometimes the frequency response is significantly closer to zero than the median. The variability or distribution of Eastern Interconnection frequency response is visibly tighter in 2007 and 2008, compared to prior years and the extreme values are further from zero than other years. Frequency data for ERCOT were only available for 2007 and 2008, so longer term trends in these data were not possible to identify.[26]

[24] ERCOT data from the NERC Resource Adequacy Application were only available for the years 2007 and 2008.

[25] NERC Long Term Reliability Assessment at http://www.nerc.com/page.php?cid=4|61.

[26] More current data identifies that ERCOT's present frequency response is approximately 640 MW/0.1 Hz.

Table 2. Yearly Trends in the Frequency Response of the Eastern, Western and ERCOT Interconnections

Year	Eastern Interconnection		Western Interconnection		ERCOT Interconnection	
	Number of Events	Median Frequency Response	Number of Events	Median Frequency Response	Number of Events	Median Frequency Response
2008	233	2469	141	1223	116	588
2007	167	2852	96	1388	78	636
2006	307	2384	76	1231	No Data	No Data
2005	136	2125	77	1761	No Data	No Data
2004	97	3376	98	1257	No Data	No Data
2003	182	2902	177	1585	No Data	No Data
2002	45	3369	111	1589	No Data	No Data

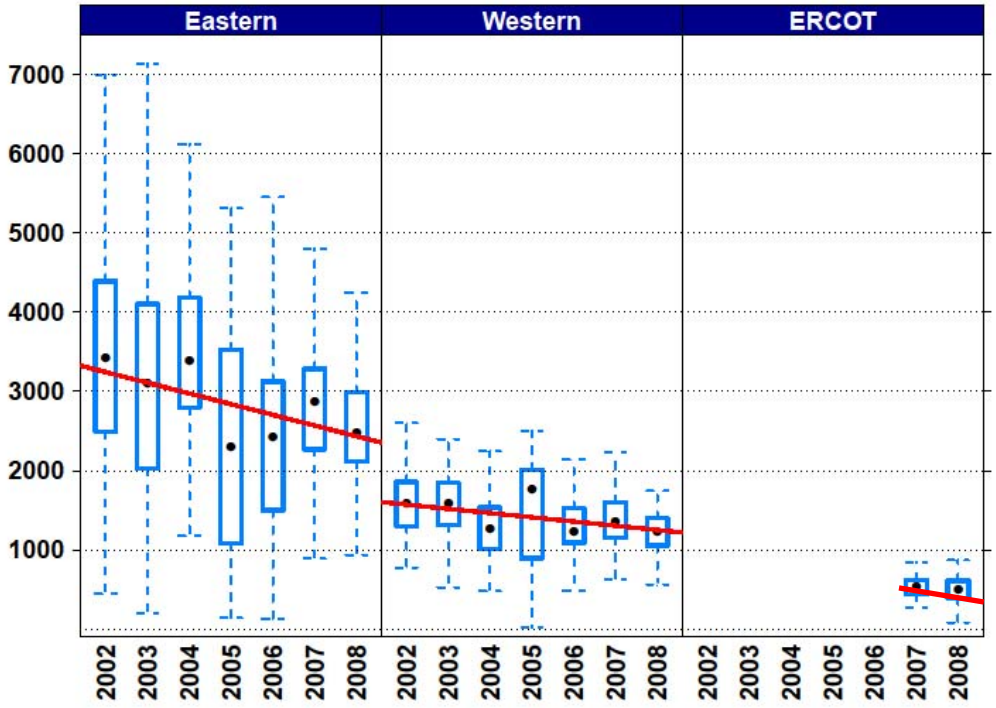

Figure 2. Yearly Trends in the Frequency Response of the Eastern, Western and ERCOT Interconnections

4. Sub-Annual Patterns in Interconnection Frequency Response Based on 1-Second Averages of Frequency

As discussed in section 2, the methods used to calculate frequency response have evolved over time. Starting in 2007, 1-second data on frequency response became available from improved monitoring technologies. For this study, we applied a consistent method, based on guidelines from the NERC Resources Subcommittee, and a consistent data set of 1-second frequency data to examine sub-annual patterns in the frequency response of all three U.S. interconnections.[27]

4.1 Monthly Frequency Response for Years 2007 and 2008

Figure 3 shows monthly medians of frequency response for each interconnection for years 2007 and 2008. The 1-second data used to calculate frequency response were not available for the first half of 2007 for the Eastern Interconnection and for the month of January 2008 for ERCOT.

For the Eastern Interconnection, August 2007 and January 2008 show median frequency responses that are further from zero than those observed in the other months. For the Western Interconnection, April 2008 shows an median frequency response that is further from zero than that observed in other months. For the ERCOT Interconnection, all monthly medians were close to the annual median. There is a very slight trend toward zero in the monthly medians for the Eastern and ERCOT Interconnections over the last half of 2008.

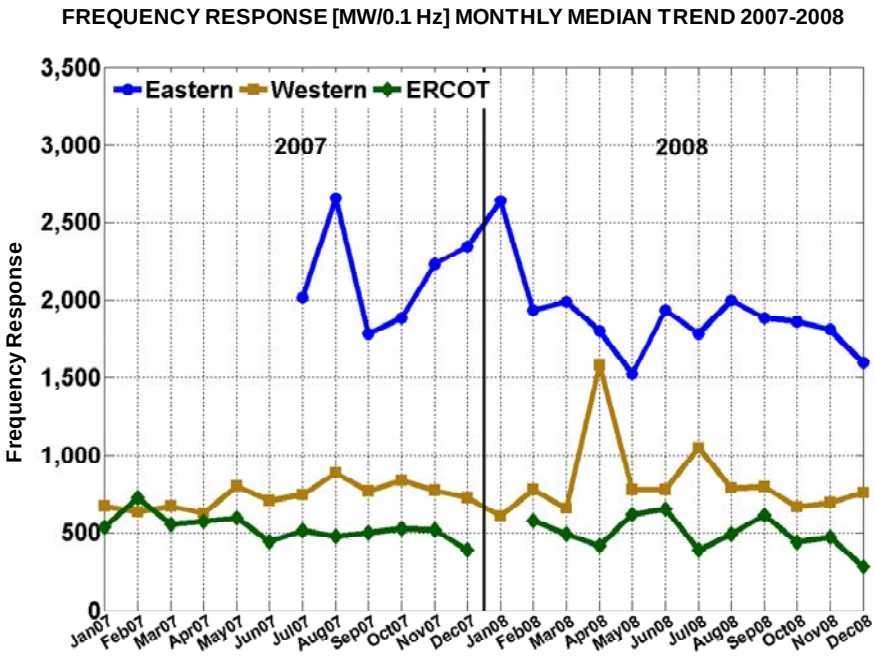

Figure 3. Median Frequency Response by Month for 2007 and 2008

[27] Section 6 presents a comparison of frequency response calculated with both 1-minute and 1-second averages of frequency.

4.2 Hourly Frequency Response for 2007 and 2008

Figure 4 shows median frequency response by hour of the day for the Eastern, Western, and ERCOT Interconnections for 2007 and 2008. Hourly values for some hours for the Eastern and ERCOT Interconnections are blank because there were no events recorded at these times or because there were no data available on events that took place at these times.

For the Eastern Interconnection in 2007, median frequency response is closer to zero during the early morning (5 AM to 8 AM) and early evening (5, 6, and 8 PM) hours.[28] In 2008, the overall pattern of values is noticeably closer to zero than it is in 2007, and there is greater volatility among the hours. The median value closest to zero in 2008 (at 1 AM) is comparable to the closest to zero median values observed in 2007.

For the Western and ERCOT Interconnections, the trends across the hours of the day are more stable than they are for the Eastern Interconnection. Lower volatility among the hours of the day holds for both 2007 and 2008. The median values for the ERCOT Interconnection during the middle of the night (1 and 2 AM) are noticeably closer to zero than the overall trend across the hours for 2008.

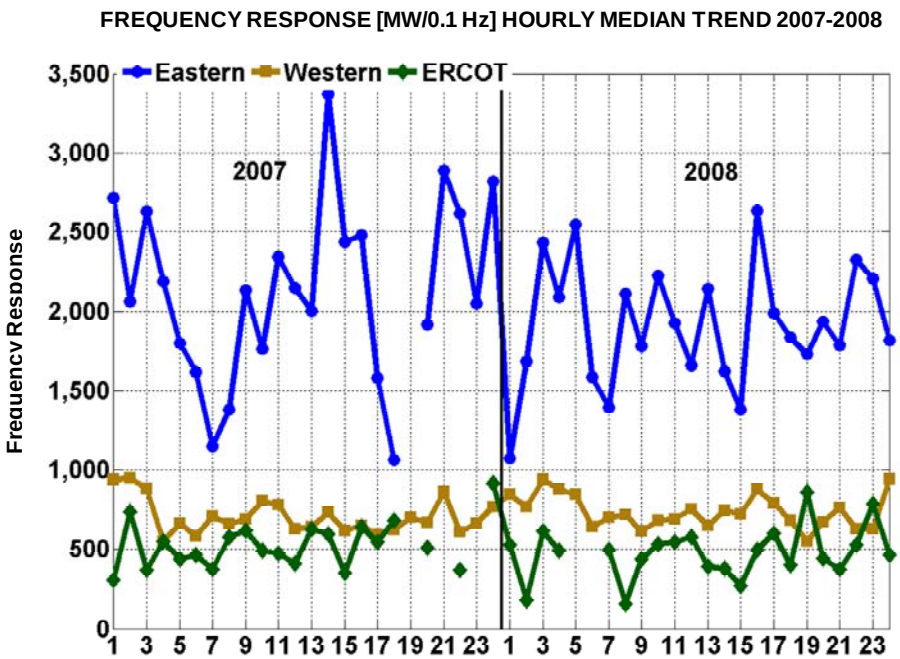

Figure 4. Median Frequency Response by Hour of the Day for 2007-2008

4.3 Frequency Response by Month and Hour and by Hour and Five Minute Period within each Hour for the Eastern Interconnection for 2007 and 2008

Figure 5 and Figure 6 cross-correlate monthly and hourly observations and hourly and five-minute observations, respectively. A color scale is used to allow for visual interpolation among

[28] All references to hours refer to hours ending.

the observations. The color scaled is anchored at approximately 2,700 MW/0.1 Hz in order to focus attention on the closest to zero observed frequency responses.

Figure 5 shows average (not median) frequency response for each hour and each month for the Eastern Interconnection for years 2007 and 2008. The numerical value of frequency response for each hour, averaged across all months, is reported on the right-hand y-axis with the number of observations in each average shown in parentheses. The numerical value of the frequency response for each month, averaged across all hours, is reported on the top x-axis with the number of observations in each average shown in parentheses. No values are shown for the first six months of 2007 due to the lack of 1-second data.

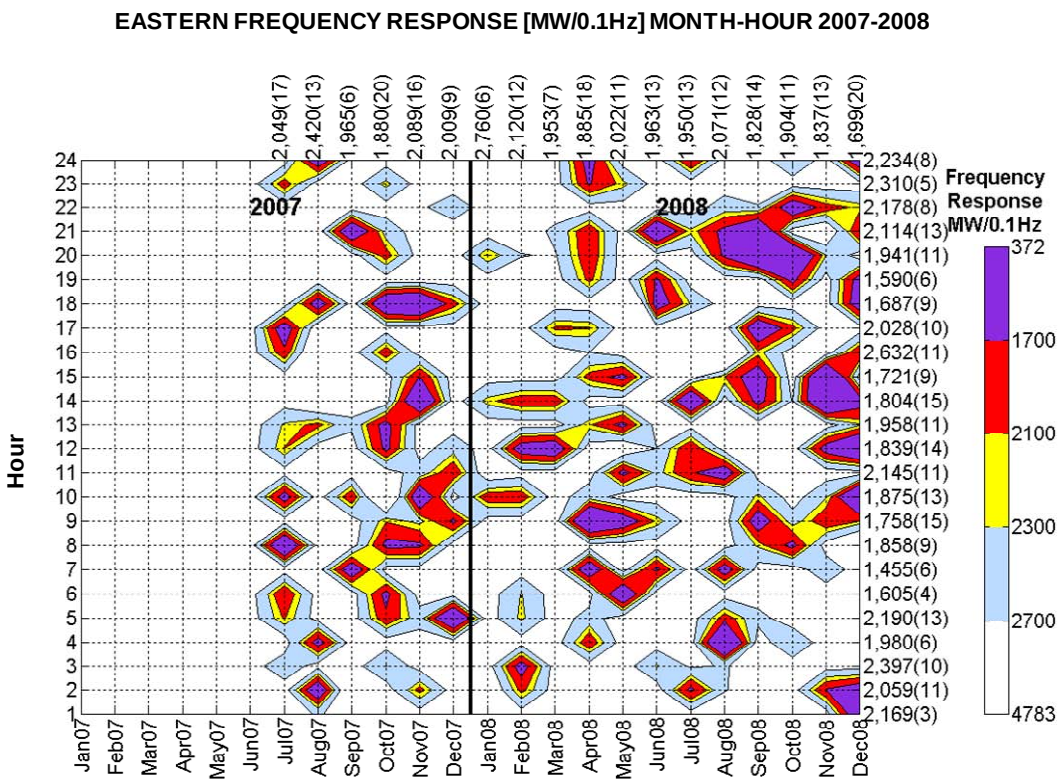

Figure 5. Eastern Interconnection Frequency Response by Month and Hour for 2007-2008

Figure 5 provides additional insight into the earlier findings discussed in conjunction with Figure 4. For 2007, the closer to zero late afternoon frequency response events took place in the fall months of October and November. In contrast, the closer to zero morning average frequency responses noted in Figure 4 are not associated with particular months. For 2008, events with closer to zero average frequency response observed in the late evening in Figure 4 are concentrated in the summer and fall months. Similarly, the events with closer to zero average frequency response observed in the middle of the night (1 AM) in Figure 4 appear to be concentrated in December. The concentration of events closer to zero average frequency response spread across the hours in the final two months of 2008 also corroborates the observation made for Figure 3.

Figure 6 shows the average frequency response for five-minute periods within each hour by hour of the day for the Eastern Interconnection for 2007 and 2008. The numerical value of frequency response, averaged across all five-minute periods, is reported on the right-hand y-axis. The number of observations contributing to the average is shown in parentheses. The numerical value of the frequency response for each five-minute period, averaged across all hours, is reported on the top x-axis. The number of observations contributing to the average is shown in parentheses.

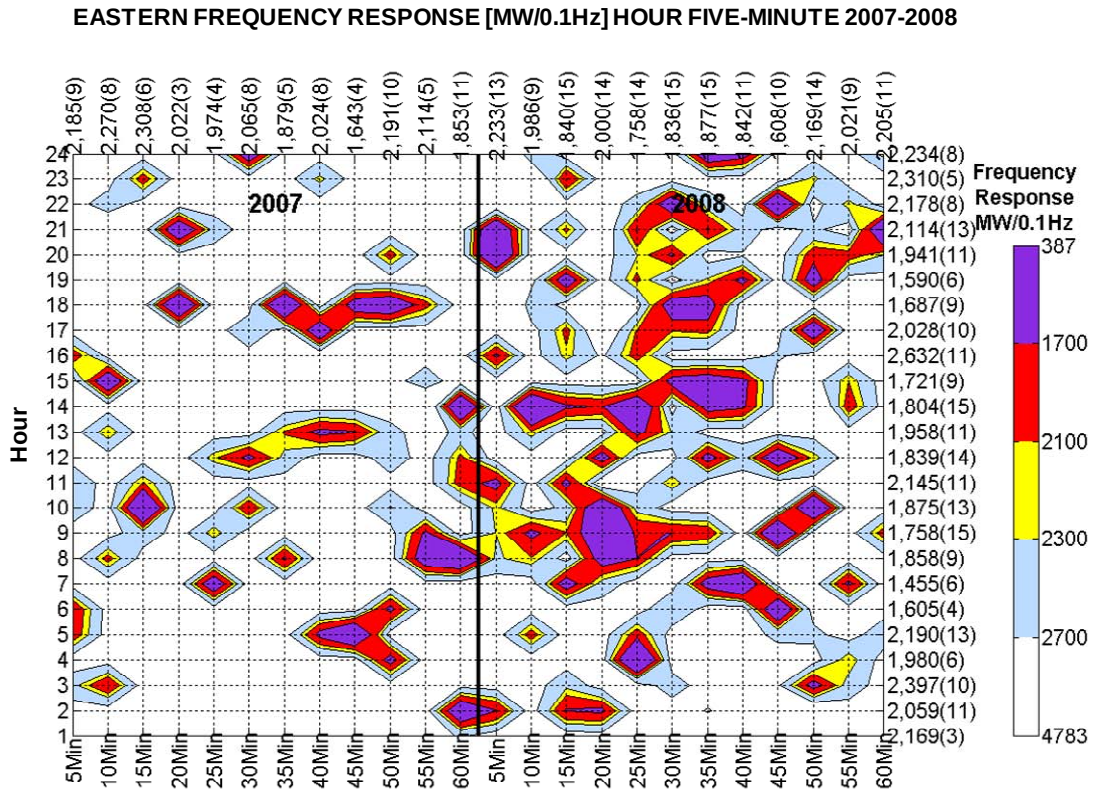

Figure 6. Eastern Interconnection Frequency Response by Hour and Five-Minute Period within each Hour for 2007-2008

Figure 6 is a first, unprecedented look at frequency response on a sub-hourly basis. For 2007, there appear to be concentrations of events with closer to zero average frequency response during the five minute periods just before the top of the hour, as well as at 6 PM. For 2008, there are more observations of closer to zero average frequency response. There are some groupings of these closer to zero averages at 2 PM, however, there are no clear patterns of averages in examining five-minute periods within the hour.

4.4 Frequency Response by Month and Hour and by Hour and Five-Minute Period within each Hour for the Western Interconnection for 2007 and 2008

Figure 7 and Figure 8 cross-correlate monthly and hourly observations and hourly and five-minute period within the hour observations, respectively. A color scale is used to differentiate among and allow for visual interpolation among observations. The color scaled is anchored at

approximately 800 MW/0.1 Hz in order to focus attention on the closest to zero observed frequency responses.

Figure 7 shows average frequency response for each hour by month for the Western Interconnection for years 2007 and 2008. The numerical value of frequency response for each hour, averaged across all months, is reported on the right-hand y-axis. The number of observations contributing to the average is shown in parentheses. The numerical value of the frequency response for each month, averaged across all hours, is reported on the top x-axis. The number of observations contributing to the average is shown in parentheses.

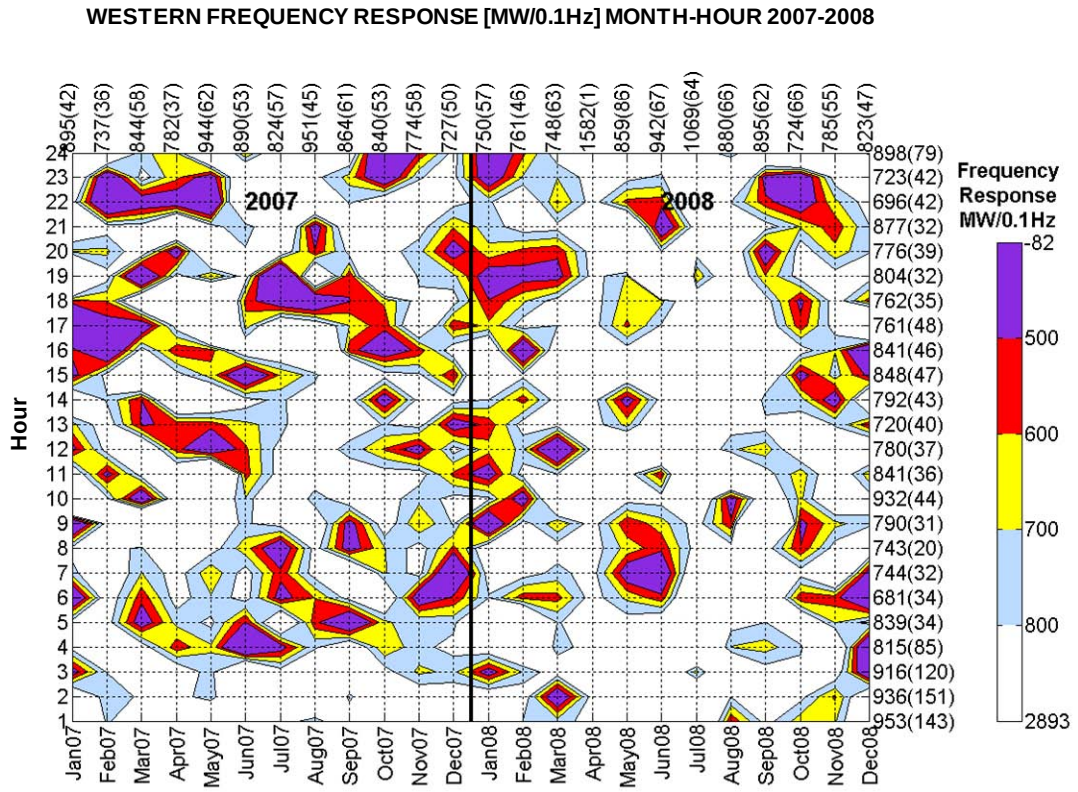

Figure 7. Western Interconnection Frequency Response by Month and Hour for 2007-2008

Figure 7 provides limited additional insight into the earlier findings discussed in conjunction with Figure 4. At first glance, the Figure provides visual corroboration that average frequency response was lower in 2007 than it was in 2008, which can also be seen in Figure 4. Beyond this, however, no clear patterns emerge that would suggest closer to zero average frequency response at particular times of the day or months over this two year period.

Figure 8 shows average frequency response for five-minute periods within each hour by hour of the day for the Western Interconnection for years 2007 and 2008. The numerical value of frequency response for each, averaged across all five minute periods, is reported on the right-hand y-axis. The number of observations contributing to the average is shown in parentheses. The numerical value of the frequency response for each five minute period, averaged across all

hours, is reported on the top x-axis. The number of observations contributing to the average is shown in parentheses.

Figure 8, like Figure 7, tends to confirm the absence of readily recognizable patterns or groupings of lower than average frequency response as a function of either hour of the day for five minute period within the hour.

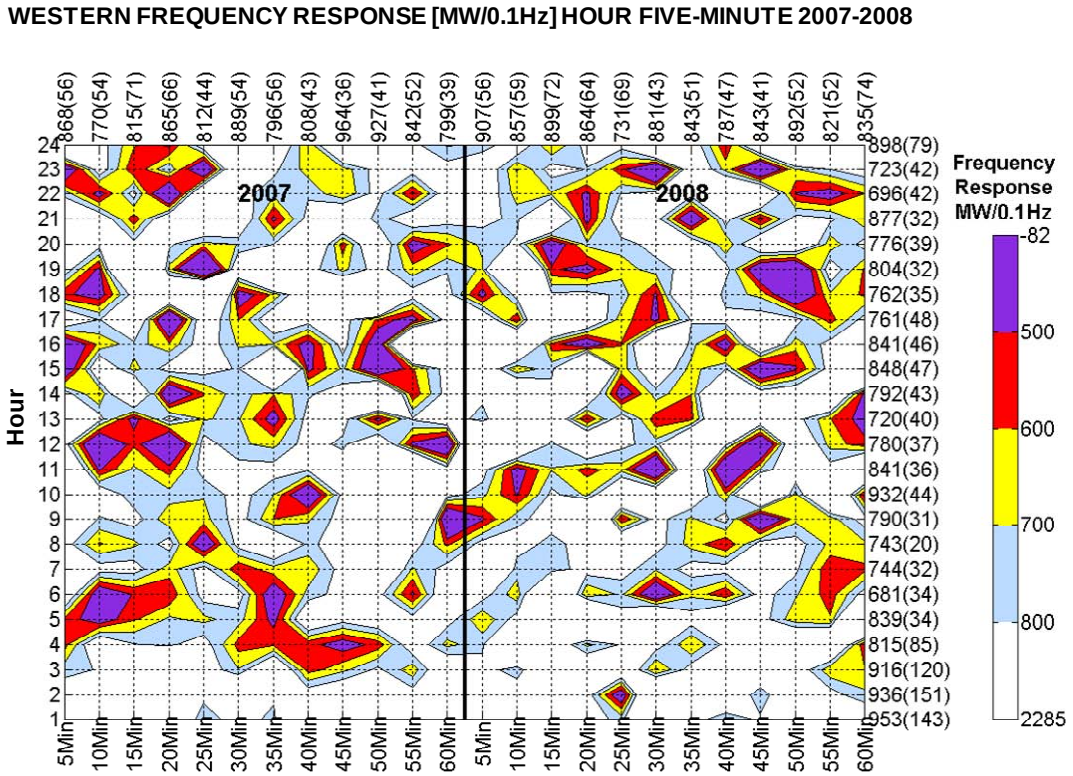

Figure 8. Western Interconnection Frequency Response by Hour and Five-Minute Period within each Hour for 2007-2008

4.5 Frequency Response by Month and Hour and by Hour and Five-Minute Period within each Hour for the ERCOT Interconnection for 2007 and 2008

Figure 9 and Figure 10 cross-correlate monthly and hourly observations and hourly and five minute period within the hour observations, respectively. A color scale is used to differentiate among and allow for visual interpolation among observations. The color scaled is anchored at approximately 600 MW/0.1 Hz in order to focus attention on the lowest observed frequency responses.

Figure 9 shows average frequency response for each hour by month for the ERCOT Interconnection for 2007 and 2008. The numerical value of frequency response for each hour, averaged across all months, is reported on the right-hand y-axis. The number of observations contributing to the average is shown in parentheses. The numerical value of the frequency response for each month, averaged across all hours, is reported on the top x-axis. The number of

observations contributing to the average is shown in parentheses. No values are shown for the first 6 months of 2007 due to the unavailability of 1 second data for use in this project.

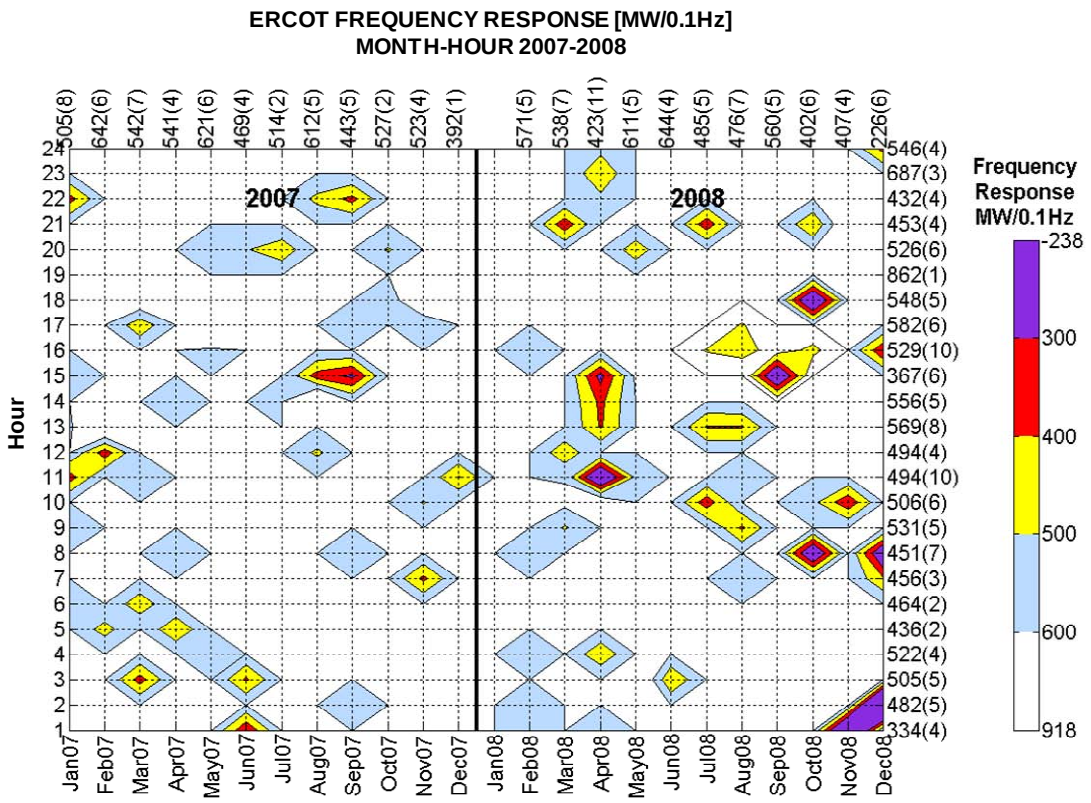

Figure 9. ERCOT Interconnection Frequency Response by Month and Hour for 2007-2008

Figure 10 shows average frequency response for five-minute periods within each hour by hour of the day for the ERCOT Interconnection for 2007 and 2008. The numerical value of frequency response, averaged across all five-minute periods, is reported on the right-hand y-axis. The number of observations contributing to the average is shown in parentheses. The numerical value of the frequency response for each five-minute period, averaged across all hours, is reported on the top x-axis with the number of observations contributing to the average in parentheses.

Figure 9 and Figure 10 are difficult to interpret because of the comparatively small number of frequency response events recorded in years 2007 and 2008. Still, both provide unprecedented detailed looks at the distribution of frequency response events and values.

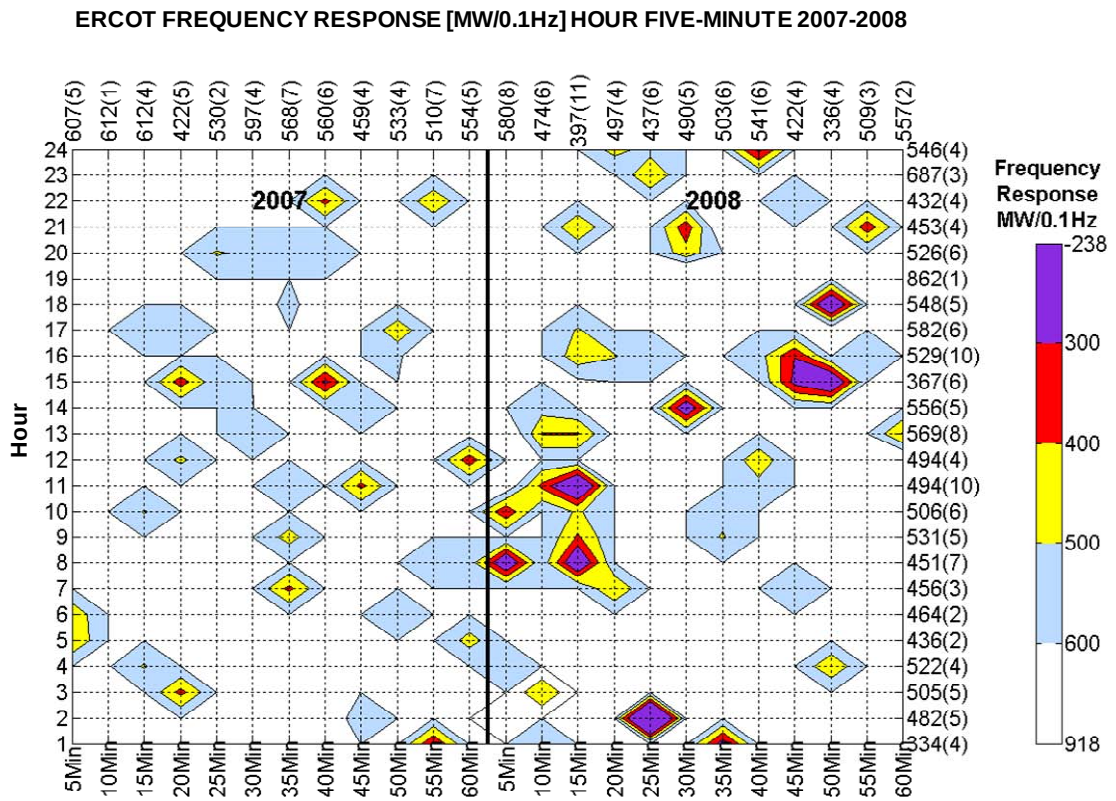

Figure 10. ERCOT Interconnection Frequency Response by Hour and Five-Minute Period within each Hour for 2007-2008

5. Sub-Annual Patterns in Interconnection RMS of Frequency Deviations Based on 1-Second Averages of Frequency

Frequency deviation is a direct measure of the balance between load and generation as reflected in differences between actual and scheduled frequency. Examining annual trends in and sub-annual patterns of frequency deviations reveals variations in the performance of the reserves deployed to manage load-generation imbalances.

Frequency deviations are expressed using the Root Mean Square (RMS) of the difference between actual and scheduled frequency. As discussed in Section 2, we established interconnection-specific RMS thresholds in order to focus on the largest RMS frequency deviations. The thresholds for the RMS frequency deviation used in this analysis are those recommended by the NERC Frequency Response drafting team. They are 22, 27, and 36 mHz for the Eastern, Western, and ERCOT Interconnections, respectively.

We identify the months of the year, the times of day, and periods within the hour when the RMS of frequency deviations exceeds thresholds for years 2007 and 2008. All analysis is based on 1-second averages of frequency on weekdays, only.

The format for the presentation follows that used in Sections 3. The median value is shown as a dot. The "box" containing the median defines the upper and lower limits of the inter-quartile range, which bound 50 percent of observed values. The "whiskers" that surround the box bounds values that are within one and one-half times the inter-quartile range above and below the box. Individual outliers that exceed this range are shown above and below the whiskers.

In a final sub-section, we present the results of our preliminary efforts to explore whether times of low frequency response (discussed in Section 3) can be correlated with times of large RMS of frequency deviations.

5.1 Eastern Interconnection

Figure 11 through Figure 14 show frequency deviations for the Eastern Interconnection by month, hour, and the five-minute period within each hour for 2007 and 2008.

Figure 11 shows that the median monthly RMS of frequency deviation for 2007 and 2008 is always less than the 22-mHz threshold. The variability in the RMS of frequency deviations is the highest for April, May, and August 2007 and for July and August 2008. The median values and distributions of RMS of frequency deviation are noticeably lower in the last two months of 2008.

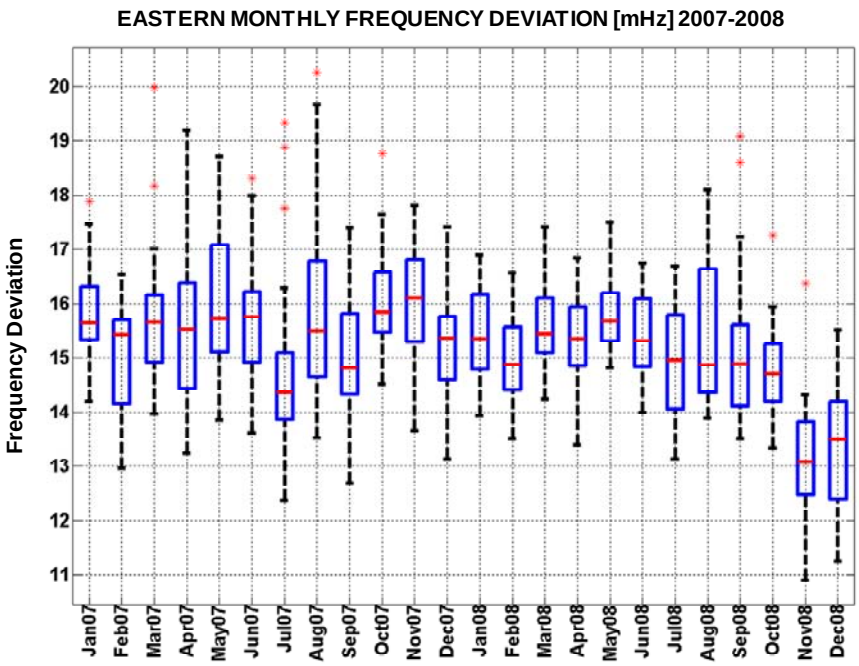

Figure 11. Eastern Interconnection Weekday RMS of Frequency Deviation by Month for 2007-2008

Figure 12 presents median RMS of frequency deviation calculated separately for each hour (Figures 11 and 12 were based on RMS of frequency deviation calculated for each day).[29] The color contouring begins at approximately 16 mHz in order to highlight larger frequency deviations.

Noticeable patterns of large frequency deviations are evident in Figure 12. First, frequency deviations are consistently largest at predictable times of the day, both during the morning hours from 6 to 7 AM and during the late evening hours 10-11 PM.

Figure 13 reinforces the observation made for Figure 12 by showing the hourly values aggregated across the months of the year. The larger median values and distributions of the RMS frequency deviation standout at 6, 7, and 8 AM, as well as at 10, 11, and 12 PM. The late evening median values in 2007 are notable because they are close to the 22 mHz threshold; in fact, a significant portion of the distribution of values, for both 2007 and 2008, is above this threshold.

[29] All references to hours refer to hours ending.

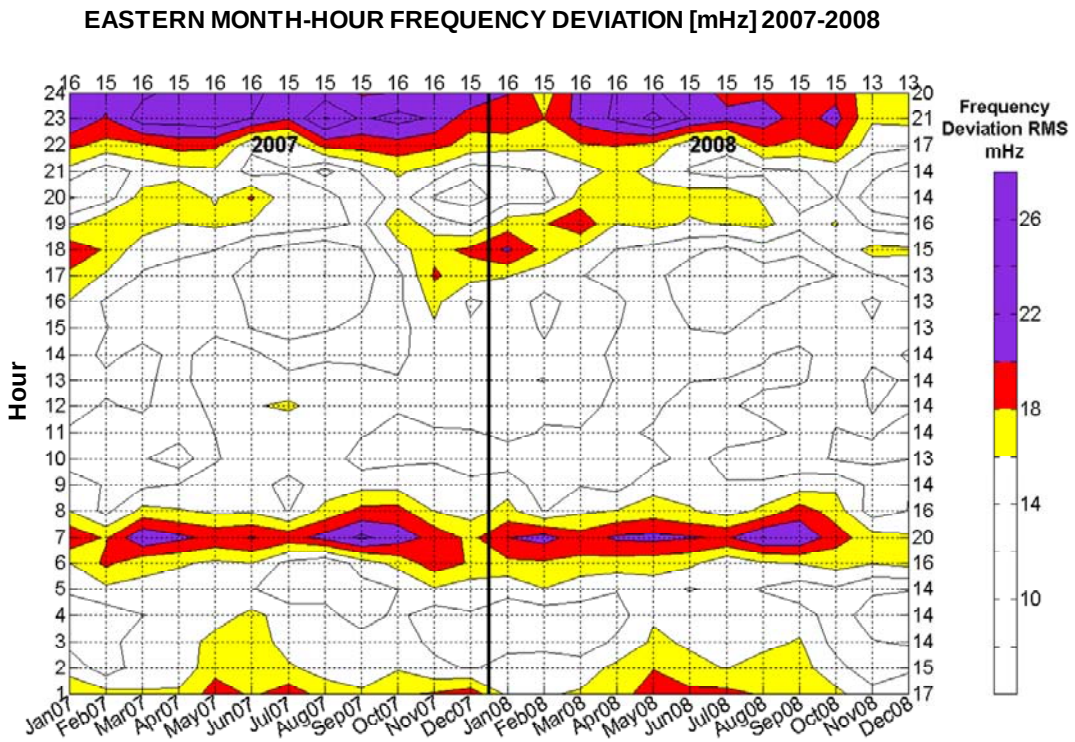

Figure 12. Eastern Interconnection Weekday RMS of Frequency Deviation by Month and Hour of the Day - 2007-2008

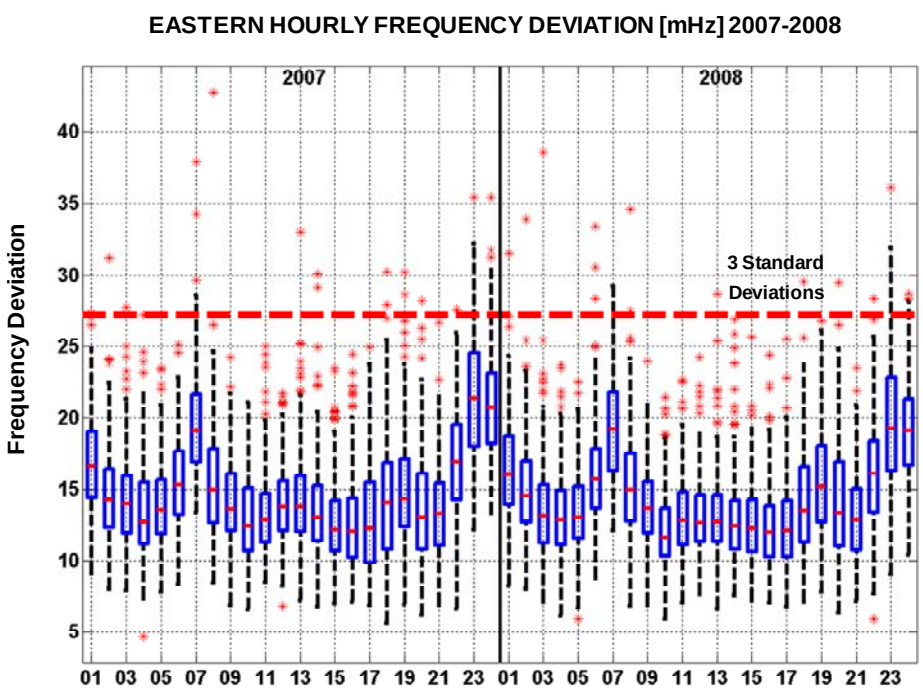

Figure 13. Eastern Interconnection RMS of Frequency Deviation by Hour of the Day– 2007-2008

Figure 14 shows the five-minute period RMS frequency deviation in each hour.

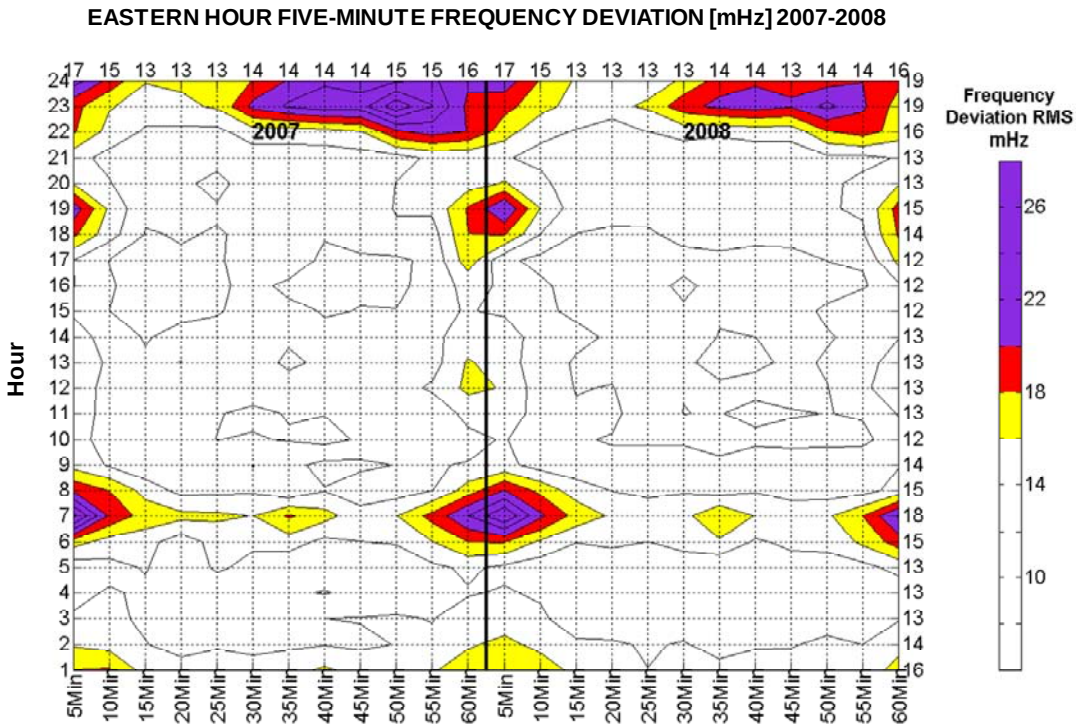

Figure 14. Eastern Interconnection RMS of Frequency Deviation by Five-Minute Period within the Hour - 2007-2008

As was done for Figure 12, the color contouring begins at approximately 16 mHz in order to highlight larger frequency deviations.

Figure 14 provides additional insight into the hourly patterns identified in Figures 12 and 13. The largest frequency deviations during the late evening hours occur during the 30 minutes prior to the top of the hour. The deviations during the morning hours are centered more narrowly during the 5 to 10 minute periods on both sides of the top of the hour.

5.2 Western Interconnection

Figure 15 through Figure 18 show frequency deviations for the Western Interconnection by month, hour, and five-minute period within each hour for 2007 and 2008.

Figure 15 shows that the median and distribution RMS of frequency deviations by month for 2007 and 2008. The distribution was broadest for April 2007. There also appears to be shift toward higher medians and broader distributions for the second half of 2008 compared earlier periods.

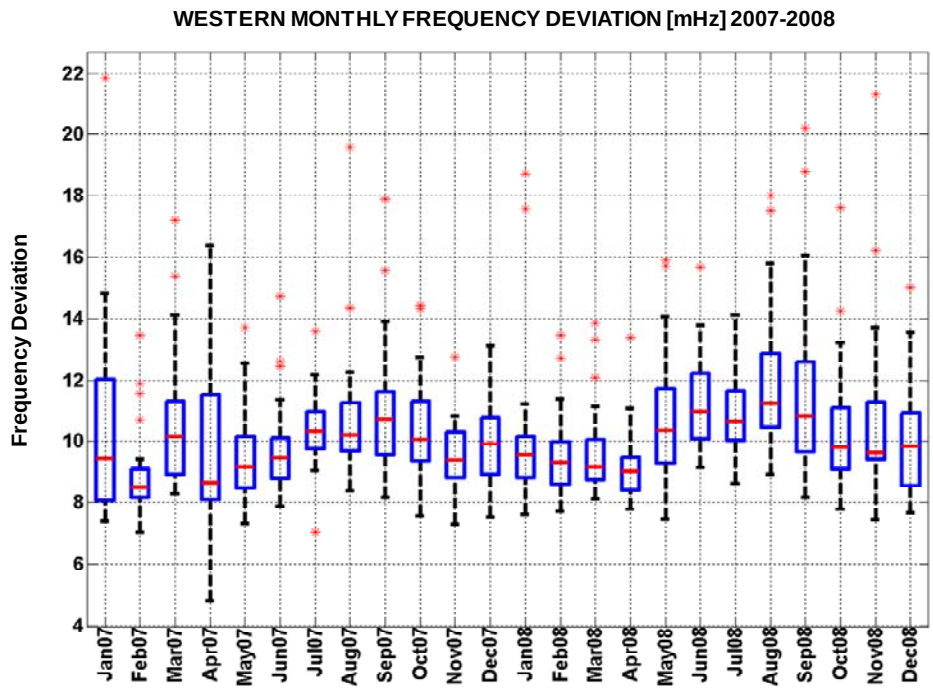

Figure 15. Western Interconnection Weekday RMS of Frequency Deviation by Month - 2007-2008

Figure 16 presents median RMS of frequency deviation calculated separately for each hour (Figure 15 was based on RMS of frequency deviation calculated for each day).

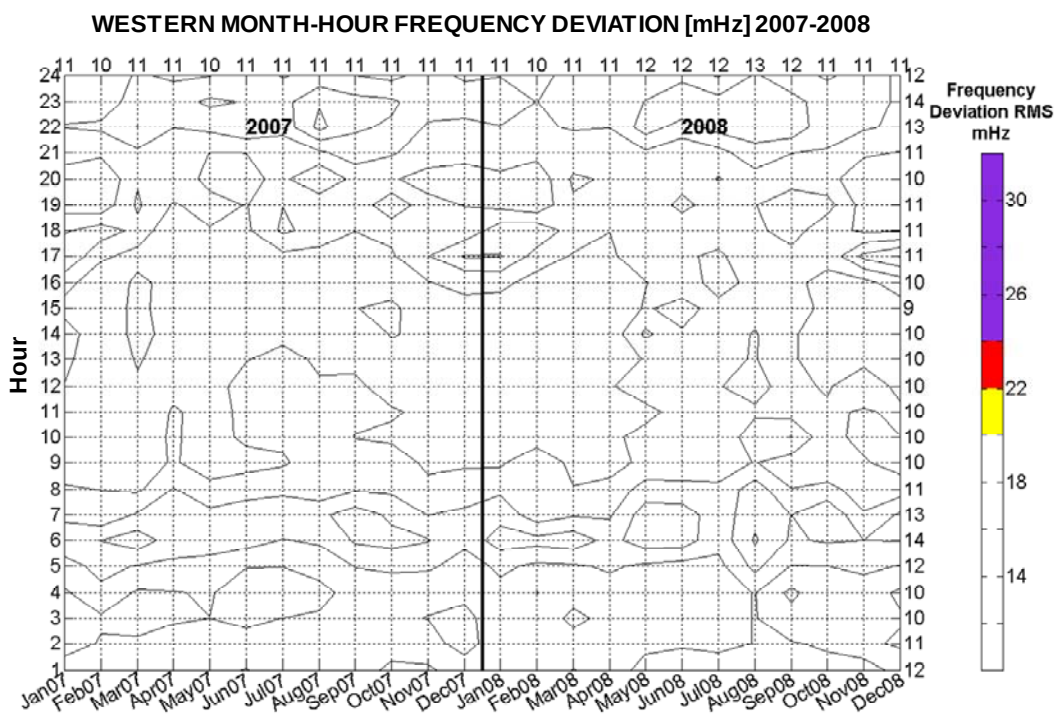

Figure 16. Western Interconnection Weekday RMS of Frequency Deviation by Month and Hour of the Day - 2007-2008

There are no large frequency deviations evident in Figure 16. The color contouring begins at approximately 20 mHz in order to highlight larger frequency deviations. All hourly values are less than the lowest value selected for color contouring. Still, hourly patterns are evident in the data and these patterns correspond roughly to those observed for the Eastern Interconnection. More investigation is recommended, possibly considering lower threshold values for the color contouring.

Figure 17 reinforces the observation made for Figure 16 by showing the hourly values aggregated across the months of the year. Again, no median value is larger than roughly 12 mHz. However, individual hourly averages are observed above the 27 mHz threshold and there is a very small number of hourly averages significantly above the threshold during the middle part of day during 2008.

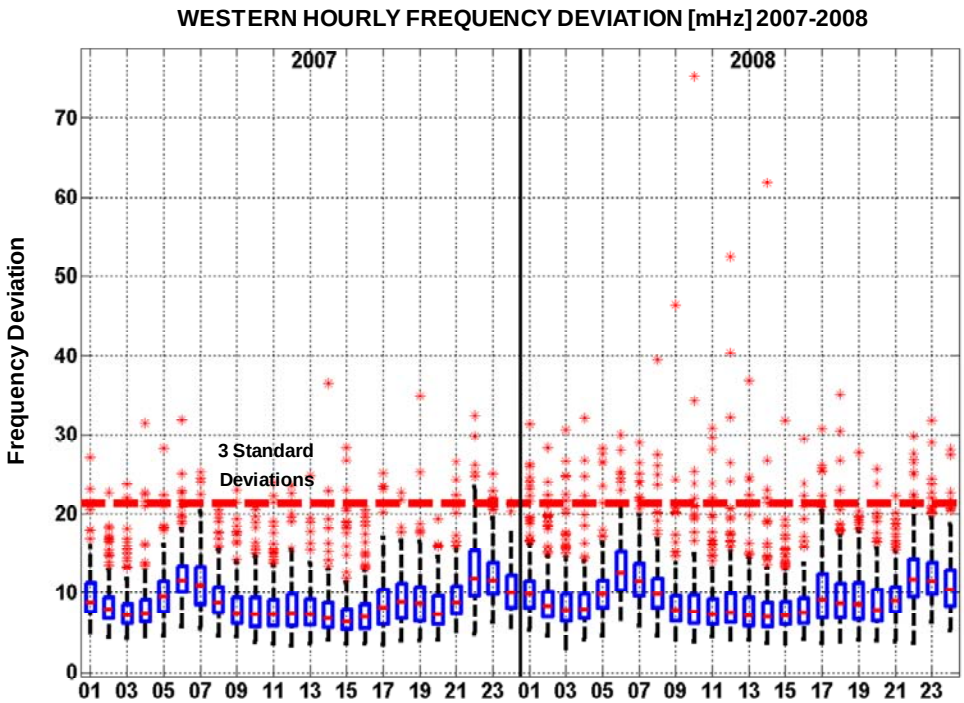

Figure 17. Western Interconnection RMS of Frequency Deviation by Hour of the Day – 2007-2008

Figure 18 presents median RMS of frequency deviation calculated separately for each five-minute period within the hour. As was done for Figure 16, the color contouring begins at approximately 20 mHz in order to highlight larger frequency deviations.

There are no noticeable large frequency deviations evident in Figure 18. All five-minute values are less than the lowest value selected for color contouring. Still, as with Figure 16, hourly patterns roughly consistent with those observed in the Eastern Interconnection are evident. Again, we recommend continued investigation of these trends.

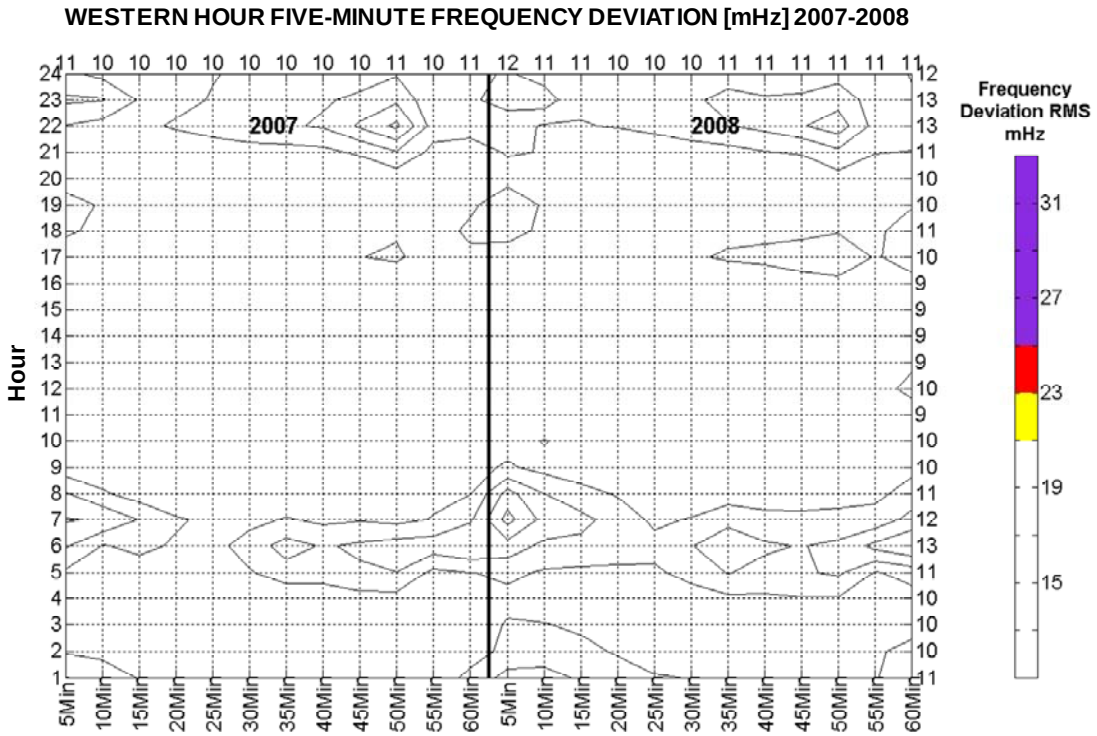

Figure 18. Western Interconnection RMS of Frequency Deviation by Hour and Five-Minute Period within the Hour – 2007-2008

5.3 ERCOT

Figure 19 through 22 show frequency deviations for the ERCOT Interconnection by month, hour, and five-minute period within each hour for 2007 and 2008.

Figure 19 shows that the median and distribution of monthly RMS of frequency deviation for 2007 and 2008 exhibits some variation by month. The medians and distributions were trending higher across months throughout 2007, but then began trending lower in 2008. The distributions of values were greatest during the last month of 2007 and the last few months of 2008.

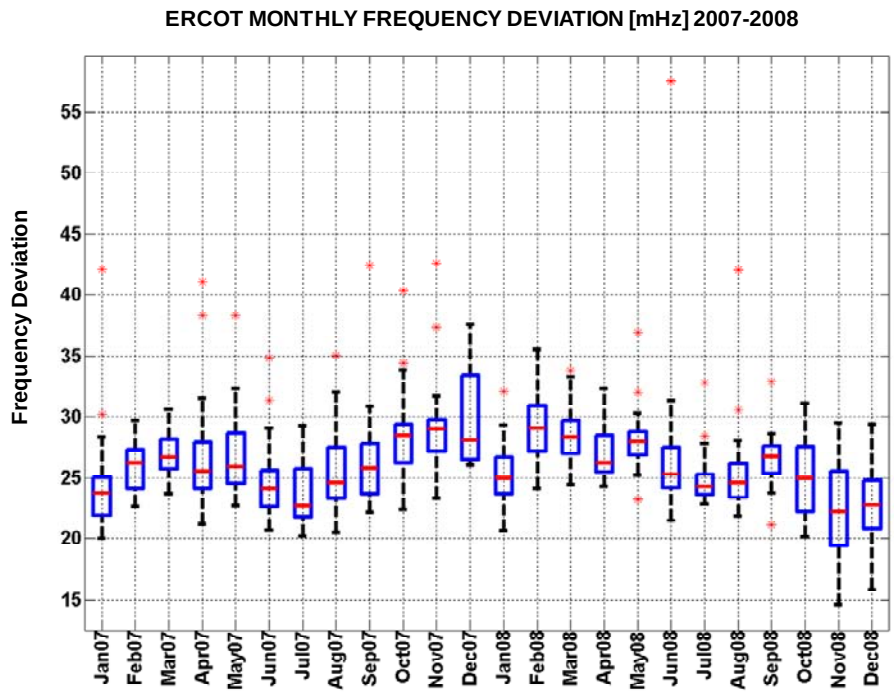

Figure 19. ERCOT Interconnection RMS of Frequency Deviation by Month - 2007-2008

Figure 20 presents median RMS of frequency deviation calculated separately for each hour.

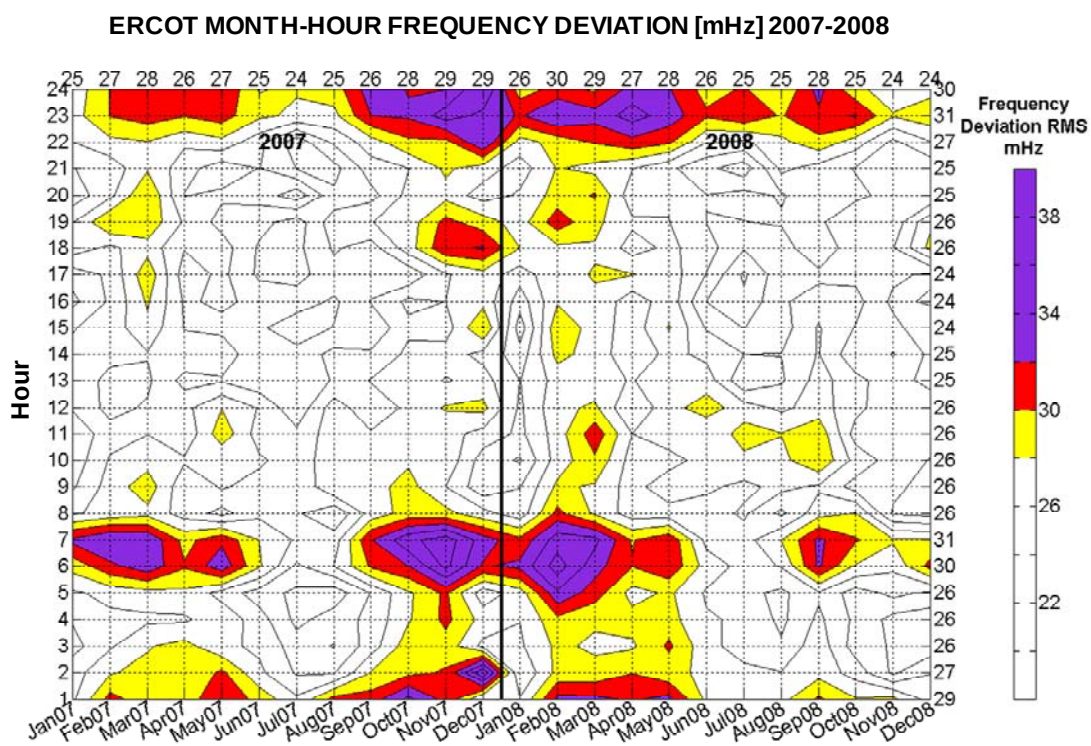

Figure 20. ERCOT Interconnection RMS of Frequency Deviation by Month and Hour of the Day – 2007-2008

The color contouring begins at approximately 28 mHz in order to highlight larger frequency deviations.

As was seen in the Eastern Interconnection, there are noticeable patterns of large frequency deviations evident in Figure 20 during the same late evening and morning hours. The largest deviations appear concentrated on both sides of the summer months in 2007. In 2008, the deviations decrease over the course of the year.

Figure 21 reinforces the observation made for Figure 20 by showing the hourly values aggregated across the months of the year. The largest medians and distributions are concentrated at 6 and 7 AM and again at 10, 11, and 12 PM.

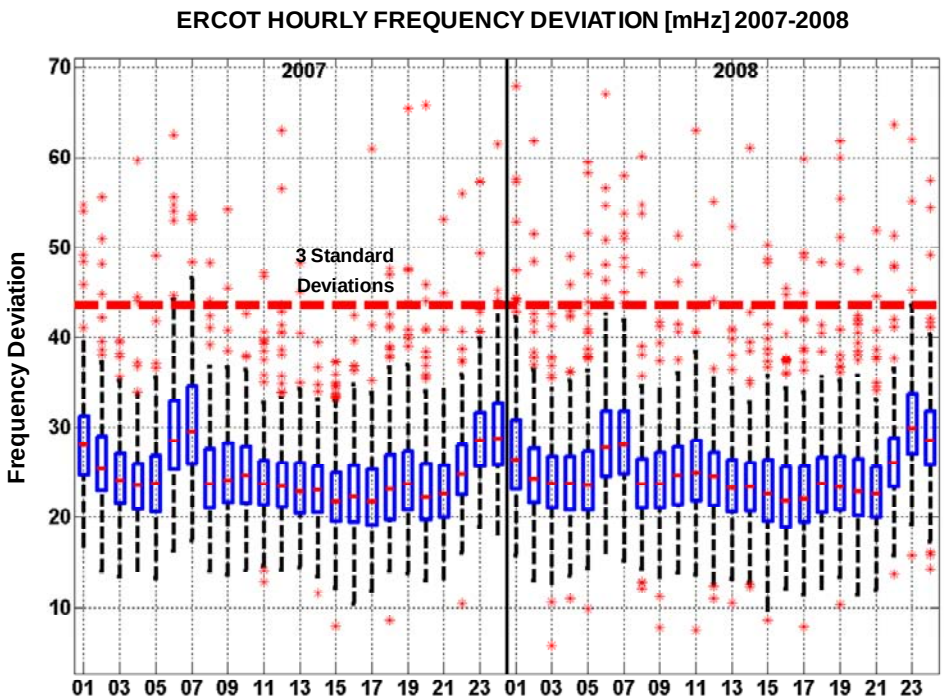

Figure 21. ERCOT Interconnection RMS of Frequency Deviation by Hour of the Day - 2007-2008

Figure 22 presents the median RMS of frequency deviation calculated separately for each five-minute period of the hour.

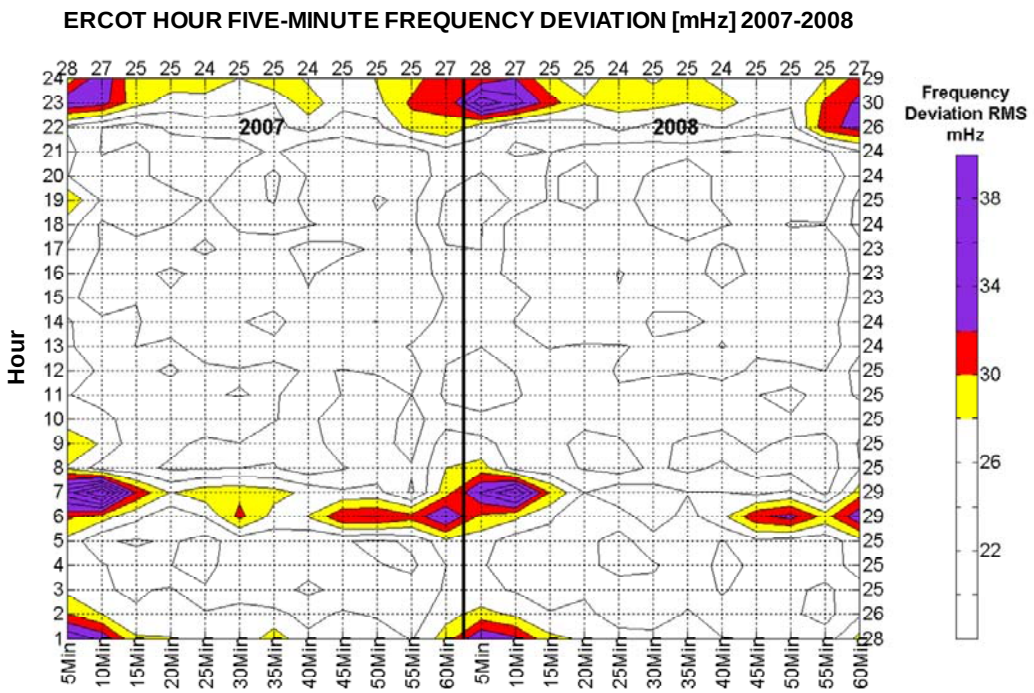

Figure 22. ERCOT Interconnection RMS of Frequency Deviation by Hour and Five-Minute Period within the Hour - 2007-2008

As was done for Figure 20, the color contouring begins at approximately 28 mHz in order to highlight larger frequency deviations. Figure 22 confirms that the large deviations observed during the morning and late evening hours occurred on both sides of the top of the hour. Generally, the largest deviations occur just after the top of the hour.

5.4 Preliminary Efforts to Correlate Frequency Response with Frequency Deviations

It is well known within the industry that there are consistent weekday periods and portions of specific hours within these periods when there are large frequency deviations. The causes of these deviations are understood to be the large ramping requirements associated with schedule changes for the now common 16-hour electricity market product, as well as rapid changes in load.

Systematically larger deviations in frequency at predictable times of the day or minutes of the hour indicate that the frequency control reserves deployed at these times do not manage the imbalances between generation and load that occur at these times as well as they do at other times. The concern is that, as a result, these may be times when the fast frequency control reserves held to respond to sudden large imbalances between load and generation may be reduced or even depleted. Hence, we undertook a preliminary examination to explore whether times of low frequency response were correlated with times of large frequency deviations.

We first conducted side-by-side visual comparisons of the color contour plots of frequency response (presented in Section 3) and frequency deviations (presented earlier in this Section).

This review was inconclusive. We were not able to visually correlate times of low frequency response with times of large frequency deviations.

We also conducted simple tabular comparisons of the recorded values of frequency response at times of the largest frequency deviations to see whether average frequency responses were systematically closer to zero at these times compared to other times of the day. Again, we did not find statistically significant correlations.

We suspect that in both instances the very limited number of frequency response events that occur during times of large frequency deviations precludes finding statistically robust correlations. Hence, we recommend continued investigation of this issue.

6. A Preliminary Examination of Aspects of Current and Evolving Methods for Calculating Interconnection Frequency Response

The methods used to calculate interconnection frequency response continue to evolve as new sources of frequency data become available and different approaches are considered for measuring the net imbalance between load and generation. This section presents preliminary examinations of three aspects of current and evolving methods for calculating frequency response. The first compares the interconnection frequency responses for 2007 and 2008 presented in Section 3 to the sum of frequency bias settings reported by balancing authorities within each interconnection. The second compares the frequency responses for 2007 and 2008 presented in Section 3, which were based on 1-minute averages of frequency, to frequency responses calculated for these same years but based on 1-second averages of frequency. The third compares the frequency responses presented in Section 3 to an independent method for estimating the frequency sensitivity of each interconnection during low frequency events.

6.1 Relationship Between the Sum of Frequency Bias Settings and Interconnection Frequency Response

Secondary frequency control actions are directed, in part, by the frequency bias term contained within the ACE control equation that is used by balancing authorities to control their generation using automatic generation control (AGC) systems. NERC standards have a requirement that "each balancing authority shall establish and maintain a frequency bias setting that is as close as practical to, or greater than, the balancing authority's frequency response."[30] There is another requirement that the balancing authority "shall have a monthly average frequency bias setting that is at least 1% of its estimated maximum generation."[31]

We summed the frequency bias settings reported by each balancing authority within an interconnection and compared this sum to the median of the interconnection's frequency responses recorded during the year based on 1-second data. This comparison allows us to examine the basis for the interconnection-wide bias adjustment factors described in Section 2.

Table 3 expresses the relationship between interconnection frequency response and the sum of frequency bias settings within the interconnection on an annual basis. We find that, for both the Eastern and Western Interconnections, the average frequency response hovers between 30-40% of the sum of balancing authority frequency bias settings within the interconnection. For the ERCOT Interconnection the percentage is considerably higher, ranging from 70% to almost 90%. These findings confirm the appropriateness of the interconnection frequency bias adjustment factors (described in Section 2) that are used to calculate frequency response (described in Section 3).[32]

[30] NERC Standard BAL-003, requirement 2.

[31] NERC Standard BAL-003, requirement 3.

[32] Note that the interconnection bias adjustment factor described in Section 2 is calculated as 1 – the ratio of median annual frequency response to the sum of frequency bias settings.

Table 3. The Relationship between the Sum of Balancing Authority Frequency Bias Settings and Interconnection Frequency Response

Year	Average Eastern Interconnection Frequency Response as a Percentage of the Sum of Balancing Authority Frequency Bias Settings	Average Western Interconnection Frequency Response as a Percentage of the Sum of Balancing Authority Frequency Bias Settings	Average ERCOT Interconnection Frequency Response as a Percentage of ERCOT Frequency Bias
2007	32%	36%	73%
2008	39%	39%	87%

6.2 Frequency Response Calculated with 1-Second Averages of Frequency and with 1-Minute Averages of Frequency

This report has sought to use the best available data to review the recent frequency performance of the three U.S. interconnections. Prior to 2007, only 1-minute averages of frequency were available. Starting in 2007, 1-second averages of frequency also became available. In this subsection, we compare median annual frequency response for 2007 and 2008 calculated using each source of frequency data.

Since the methods used to calculate frequency response using 1-second averages of frequency differ from those used to calculate it using 1-minute averages of frequency (see Section 2), it is important to recognize that these differences will affect the resulting estimates of frequency response. The differences include:

1. The number of events that are identified; and
2. The process of estimating change in frequency associated with each event

Therefore, the purpose of this comparison is simply to illustrate globally the extent to which the methods lead to different estimates. The task of identifying the relative contributions of each difference and further refinement of these methods is recommended for future studies.

Table 4 compares median annual frequency response for each interconnection for 2007 and 2008 using both sets of frequency data. We find that, using the methods outlined in Section 2, the median frequency response calculated with 1-second averages of frequency is always closer to zero than that calculated with 1-minute averages of frequency. For the Eastern and ERCOT Interconnections, the number of events contributing to the median is also smaller using the 1-minute averages. For the Western Interconnection, the number is larger to a significant extent.

Methods for calculating frequency response based on 1-second averages of frequency are in an initial state of development and this comparison contributes to the evolution of these methods. The text box contains a comparison of annual RMS of frequency deviation (weekdays, only) using 1-minute and 1-second averages of frequency.

Table 4. Comparison of Median Annual Frequency Response Calculated with 1-Second and 1-Minute Frequency Data

	1-Minute	1-Second	delta%
Eastern			
2008			
Number of Events	233	150	-36%
Median Frequency Response	2,469	1,890	-23%
2007			
Number of Events	167	81	-52%
Median Frequency Response	2,852	2,056	-28%
Western			
2008			
Number of Events	141	56	-60%
Median Frequency Response	1,223	1,021	-17%
2007			
Number of Events	96	53	-45%
Median Frequency Response	1,388	860	-38%
ERCOT			
2008			
Number of Events	116	65	-44%
Median Frequency Response	588	491	-16%
2007			
Number of Events	78	54	-31%
Median Frequency Response	636	536	-16%

6.3 The Sensitivity of Interconnection Frequency to Changes in Net ACE During Low Frequency Events

We explored a complement to the traditional method for calculating interconnection frequency response that is an empirically-based estimate of the sensitivity of interconnection frequency to changes in net ACE during low frequency events. Low frequency events are identified as times when the frequency of an interconnection falls below a threshold value.[33] We then compared the change in frequency to the change in the net ACE of the interconnection at the time of each event. The slope of the linear correlation between these two values provides an empirically-based estimate of the sensitivity of interconnection frequency to changes in interconnection net ACE in Hertz per 1000 Megawatt for low frequency events.

We estimated the slope in two ways: first, by fixing the intercept at zero; second by allowing the data, alone, to determine a best fit. The first method is motivated by the recognition that, in theory, the intercept resulting from this linear relationship should always pass through zero. The second method is motivated by the recognition that the correlation is based on only a subset of frequency events, namely, those greater than a threshold deviation (as defined in Section 2) and that measurement error is introduced when using averages of frequency (in this, case 1-minute).

[33] As documented in Section 2, the thresholds are -36 mHz for both the Eastern and Western Interconnection and -70 mHz for ERCOT.

Separate estimates were made for on-peak and off-peak hours. The definition for on-peak hours is hours ending 7-22 Central for the Eastern Interconnection, hours ending 7-22 Pacific for the Western Interconnection, and hours ending 8-22 Central for ERCOT. As noted, all calculations were made using 1-minute averages of frequency.

Figures 23-25 plot changes in frequency with changes in Net ACE for low frequency events for on-peak and off-peak periods for the Eastern, Western, and ERCOT Interconnections, respectively. Tables 5-7 summarize the corresponding slope estimates and present statistics on how well the estimates fit the data. Note that the coefficient of determination or R^2 associated with the regressions that force a zero intercept cannot be compared to the R^2 associated with regressions that do not force a zero intercept. In the first regression, the R^2 measures how the regression fits the data compared to the assumption that the data are zero. In the second regression, the R^2 measures how the regression fits the data compared to the assumption that the data are equal to the mean value. In other words, the R^2 from the two regressions are comparable only in the special instance when the mean value of the data is zero.

Several trends are evident in the slope estimates. First, looking across the interconnections, the sensitivity values are highest for the ERCOT Interconnection, followed by the Western Interconnection, and then the Eastern Interconnection, which is consistent with the relative sizes of the interconnections to one another.

Second, the values across the years are relatively stable. For the Eastern Interconnection, there is a slight downward trend in the off-peak values. For the Western Interconnection, there is more variability in the off-peak values than in the on-peak values.

Third, the relationship between the values for the on-peak and off-peak periods varies by interconnection. For the Eastern and ERCOT Interconnection, they are close to one another. For the Western Interconnection, the off-peak values are greater than the on-peak values.

Fourth, the choice of slope estimation method has a significant effect. The values calculated when restricting the slope to pass through a zero intercept are typically an order of magnitude greater than those calculated without this restriction. As noted, above, it is not appropriate to compare the R^2 associated with the regressions that force a zero intercept to the R^2 associated with regressions that do not force a zero intercept

This is an exploratory analysis of a new method for examining the frequency sensitivity of the interconnections. More research is recommended to refine the data and analysis methods to increase understanding of these trends and their implications for reliability.

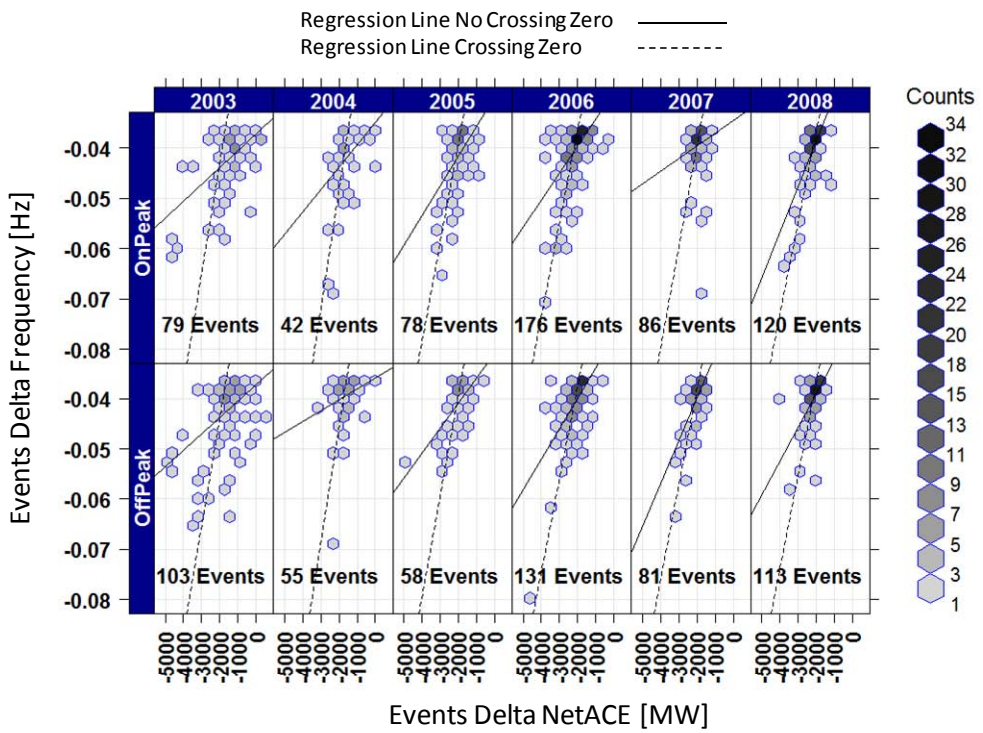

Figure 23. Sensitivity of Eastern Interconnection Frequency to Changes in Net ACE for Low Frequency Events (< -36 mHz)

Table 5. Eastern Interconnection Frequency Sensitivity to Changes in Net ACE for Low Frequency Events (< -36 mHz)

ON PEAK		2003	2004	2005	2006	2007	2008
Best Fit with Intercept Crossing Zero	Slope [Hz/1000 MW]	0.0228	0.0239	0.0198	0.0185	0.0197	0.0183
	R^2 *	0.73	0.75	0.79	0.79	0.80	0.80
Best Fit with Intercept Not Crossing Zero	Slope [Hz/1000 MW]	0.0009	0.0022	0.0029	0.0021	0.0026	0.0049
	R^2 *	0.02	0.05	0.40	0.06	0.06	0.18
OFF PEAK		**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Best Fit with Intercept Crossing Zero	Slope [Hz/1000 MW]	0.0233	0.0234	0.0201	0.0185	0.0191	0.0185
	R^2 *	0.78	0.82	0.83	0.77	0.85	0.77
Best Fit with Intercept Not Crossing Zero	Slope [Hz/1000 MW]	0.0023	0.0016	0.0045	0.0055	0.0076	0.0073
	R^2 *	0.06	0.05	0.14	0.23	0.26	0.13

* Note that R^2 cannot be compared between the two regression methods used

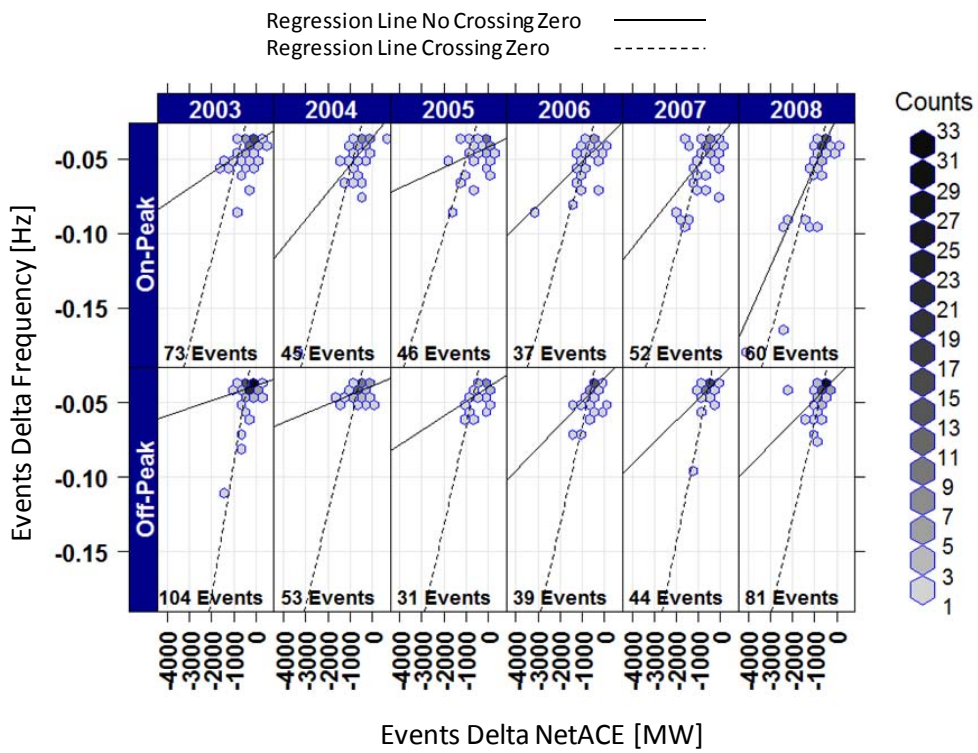

Figure 24. Sensitivity of Western Interconnection Frequency to Changes in Net ACE for Low Frequency Events (< -36 mHz)

Table 6. Western Interconnection Frequency Sensitivity to Changes in Net ACE for Low Frequency Events (< -36 mHz)

ON PEAK		2003	2004	2005	2006	2007	2008
Best Fit with Intercept Crossing Zero	Slope [Hz/1000 MW]	0.0576	0.0591	0.0500	0.0587	0.0555	0.0609
	R^2 *	0.49	0.70	0.38	0.77	0.74	0.80
Best Fit with Intercept Not Crossing Zero	Slope [Hz/1000 MW]	0.0099	0.0068	0.0022	0.0145	0.0034	0.0050
	R^2 *	0.29	0.09	0.01	0.26	0.01	0.00
OFF PEAK		**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Best Fit with Intercept Crossing Zero	Slope [Hz/1000 MW]	0.0889	0.0673	0.0651	0.0695	0.0720	0.0666
	R^2 *	0.58	0.75	0.50	0.78	0.82	0.83
Best Fit with Intercept Not Crossing Zero	Slope [Hz/1000 MW]	0.0017	0.0073	0.0066	0.0116	0.0082	0.0026
	R^2 *	0.01	0.22	0.06	0.15	0.11	0.01

* Note that R^2 cannot be compared between the two regression methods used

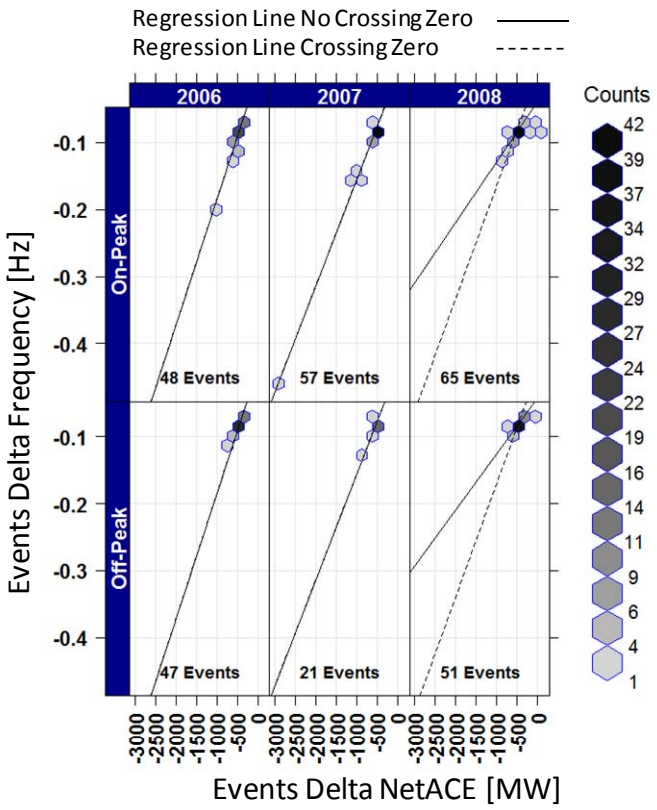

Figure 25. Sensitivity of ERCOT Interconnection Frequency to Changes in Net ACE for Low Frequency Events (< -75 mHz)

Table 7. ERCOT Interconnection Frequency Sensitivity to Changes in Net ACE for Low Frequency Events (< -75 mHz)

ON PEAK		2006	2007	2008
Best Fit with Intercept Crossing Zero	Slope [Hz/1000 MW]	0.186	0.157	0.169
	R^2 *	0.80	0.82	0.72
Best Fit with Intercept Not Crossing Zero	Slope [Hz/1000 MW]	0.186	0.157	0.132
	R^2 *	0,82	0.82	0.45
OFF PEAK		**2006**	**2007**	**2008**
Best Fit with Intercept Crossing Zero	Slope [Hz/1000 MW]	0.186	0.157	0.170
	R^2 *	0.82	0.89	0.76
Best Fit with Intercept Not Crossing Zero	Slope [Hz/1000 MW]	0.186	0.157	0.052
	R^2 *	0,82	0.89	0.47

* Note that R^2 cannot be compared between the two regression methods used

7. Summary and Conclusions

Applying consistent methods and data, we confirm and extend industry reports that frequency response has been declining within the Eastern and Western Interconnections. We document anecdotal observations that, on weekdays, large RMS values of frequency deviations take place at predictable periods during the day and within the hour. We did not find a statistically significant relationship between the times of larger RMS of frequency deviation and times of lower frequency response, but recommend this topic for future investigation. We also conducted preliminary investigations of selected, emerging topics on the measurement of frequency response.

While we have attempted to use the latest methods and best available data to conduct this review, we recognize that the methods and data continue to improve. Our review has sought to point to a number of areas where further investigation is warranted.