Historical Frequency Trends Technical Brief

ERS Framework[1] Measures 1, 2 & 4 – Historical Frequency Analysis

The NERC Planning Committee and Operating Committee jointly created the Essential Reliability Services Task Force (ERSTF) to consider reliability issues that may result from the changing generation resource mix, resulting in the development of essential reliability services (ERS) measures for examination and monitoring to identify trends. The ERSTF was converted into the ERS Working Group (ERSWG) and charged with identifying, evaluating, and developing "Sufficiency Guidelines" for each quantifiable measure.

The ERSWG frequency measures are intended to monitor and identify trends in frequency response performance as the generation mix continues to change. The holistic frequency measure, called Measure 4 in ERSWG reports, tracks phases of frequency performance for actual disturbance events in each interconnection (e.g., initial frequency rate of change, and timing of the arresting and recovery phases). Other measures look at components of this coordinated frequency response, such as the amount of synchronous inertial response (SIR, Measure 1) and the initial rate of change in frequency following the largest contingency event (RoCoF, Measure 2). This paper describes the analysis being conducted by the NERC Resources Subcommittee (RS) for these measures using historical data.

Background

Frequency support is the response of generators and loads to maintain the system frequency in the event of a system disturbance. Frequency support is provided through the combined interactions of synchronous inertia (traditionally from generators such as natural gas, coal, and nuclear plants as well as from motors at customer locations) and frequency response (from a wide variety of generators and loads). Working in a coordinated way, these characteristics arrest and eventually stabilize frequency. A critical issue is to stabilize the frequency before it falls below underfrequency load shedding values or rises above overfrequency relay trip settings.

It is important to understand that inertia and frequency response are properties of the interconnection (not to each balancing area individually) and these properties have different characteristics for each interconnection. For example, if changes to the resource mix alter the relative amounts of synchronous inertial response or frequency response, various mitigation actions are possible (such as obtaining faster primary frequency response from other generators or loads) to maintain or improve overall frequency support.

[1] Essential Reliability Services Working Group, Measures Framework Report, November 2015

Trends in the frequency measures can be analyzed using historical data. This document discusses each frequency measure and describes the analysis being conducted by the NERC RS using historical data. The results of this analysis by the NERC RS will be reflected in the NERC State of Reliability (SOR) Report.
The ERSWG is also working with the NERC RS on forward-looking projections for these frequency measures, and when available, these planning methods will be discussed in a separate Technical Brief.

Measure 4 Frequency Performance after Large Contingency

Measure 4 is a holistic measure that tracks the system frequency performance following large contingency events that have actually occurred in each interconnection. On a quarterly basis, the NERC RS selects the events and calculates a number of submeasures that reflect the minimum/maximum frequency points and the timing of the minimum/maximum frequencies and recovery period. For Measure 4, multiple years of these values will be monitored to highlight trends that could be due to changes in the generation mix or other factors.

The actual events that are being analyzed by the NERC RS are referred to as Metric 4 events. (The NERC RS was previously using Metric 4 to select significant events, and the naming similarity of Measure 4 and Metric 4 is purely coincidental.)

Metric 4 events are used for the annual NERC State of Reliability Report that performs statistical analyses of frequency response performance trends at the interconnection level. The criteria shown in Table 1 are used to select events for analyses.

Table 1. Metric 4 Event Selection Criteria

Interconnection	Δf_{AC} (mHz) ***or***	>= MW Loss
Eastern	36 mHz	800 MW
Western	70 mHz	700 MW
Texas	80 mHz	450 MW
Québec	300 mHz	450 MW

Measure 4 consists of a number of submeasures that use a common nomenclature for identifying points and values in frequency response traces. Figure 1 shows two frequency traces after the loss of a generation resource and the naming conventions commonly used in event analysis are indicated on the figure. The event starts at time t_0. Value A is the average frequency from t-16 to t-2 seconds. Point C is the lowest frequency point observed in the first 12 seconds. Value B is the average frequency from t+20 to t+52 seconds. Point C' occurs if and when the frequency (t+52 to t+300 seconds) falls below either Point C or Value B.

Frequency response values are generally calculated as a ratio of the megawatts affected in the event and a frequency deviation. In this document, these values are shown as a positive value in MW/0.1Hz.

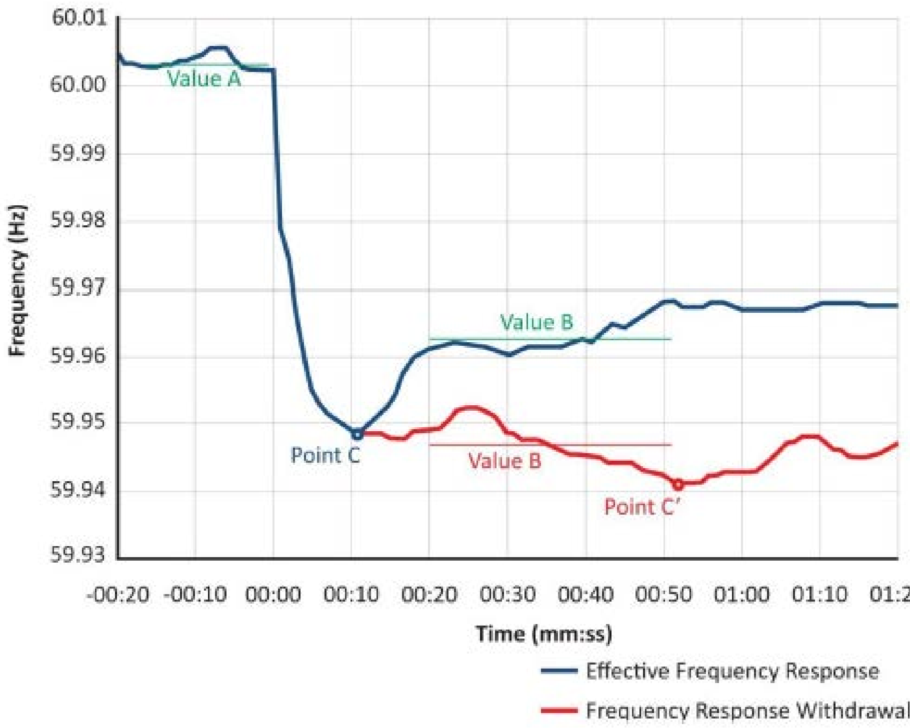


Figure 1. Frequency traces after loss of a generation resource

The NERC RS uses "box-and-whisker" plots for the submeasures of Measure 4. In the plots, the central value (the red line and number) is the median value, the top and bottom edges of the box (in blue) are the 25th and 75th percentiles, and the whiskers correspond to +/- 2.7 standard deviations (i.e., 2.7 sigma, representing 99.3% coverage of all the events in the set, assuming the data are normally distributed). If necessary, the RS can adjust the whiskers to show a different coverage, but all figures in this document use these default settings. Individual outliers (red crosses) are events outside of the 99.3% coverage.

For the plots shown in this document, loss of load events are excluded. All plots show only the loss of generation events. The NERC RS also analyzes loss of load events in an analogous way, but such events are less common than loss of generation events and are omitted here to avoid confusion.
Measure 4 contains analyzed events that occurred between December 2015 and November 2016. Table 2 shows the number of Metric 4 events during this period for all interconnections.

Table 2. Metric 4 Number of Events

Interconnection	Number of Events
Eastern	65
Western	46
Texas	51
Québec	47

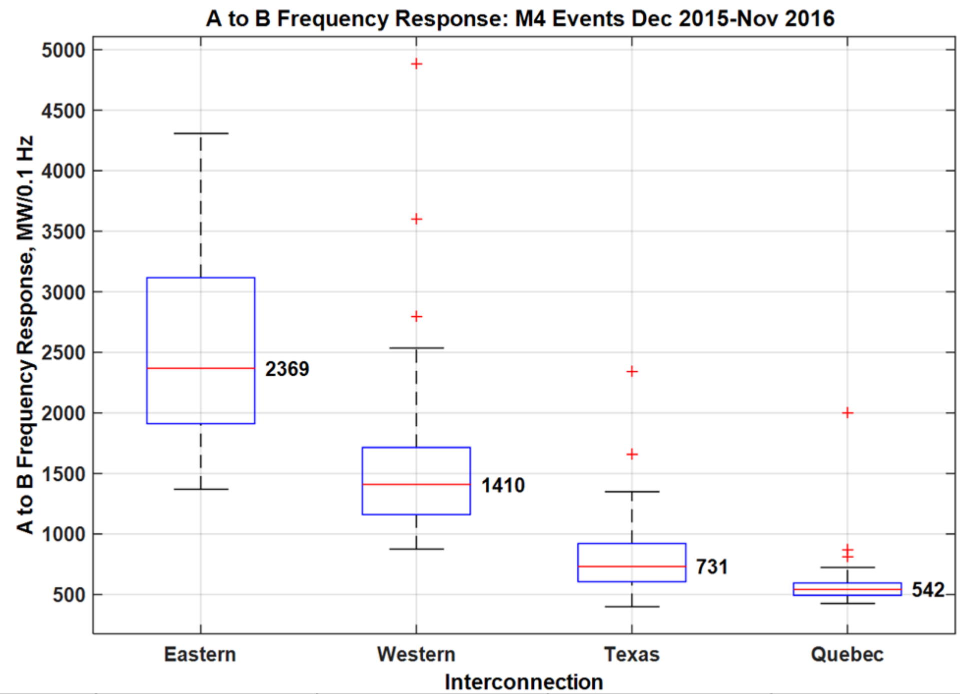
Submeasure 4.1 A to B Frequency Response

The **A to B Frequency Response** reflects the initial primary frequency response for the interconnection. This submeasure is the ratio of net MW lost to the difference between Value A and Value B frequencies.

$$\textit{Frequency Response A to B} = \frac{\textit{Generation (or Load) Lost (MW)}}{\textit{Frequency A} - \textit{Frequency B}}$$

An increasing trend over time indicates that frequency response is improving for the interconnection. Histogram distributions show the variability of the interconnection response for multiple individual events. Figure 2 shows boxplots for Submeasure 4.1, for analyzed events that occurred between December 2015 and November 2016. The median A to B frequency in MW/0.1 Hz is listed next to the centerline (red line) of each boxplot. The table under the plot shows average generation loss in MW for the analyzed events in each interconnetcion.

The boxplots are shown in the same figure for convenience, but since all four interconnections are of different sizes with very different resources and characteristics, this is for purposes of illustration and not for comparison. As more data becomes available, each interconnection will be analyzed separately to show their individual trends across multiple years. The average MW loss for the time period under study should be considered when evaluating individual interconnection trends. The same approach and caveats apply to the boxplots for Submeasures 4.2 through 4.7 discussed below.



Avg. MW Loss	938	734	601	740

Figure 2. A to B Frequency Response (Submeasure 4.1) for Analyzed Events between December 2015 and November 2016

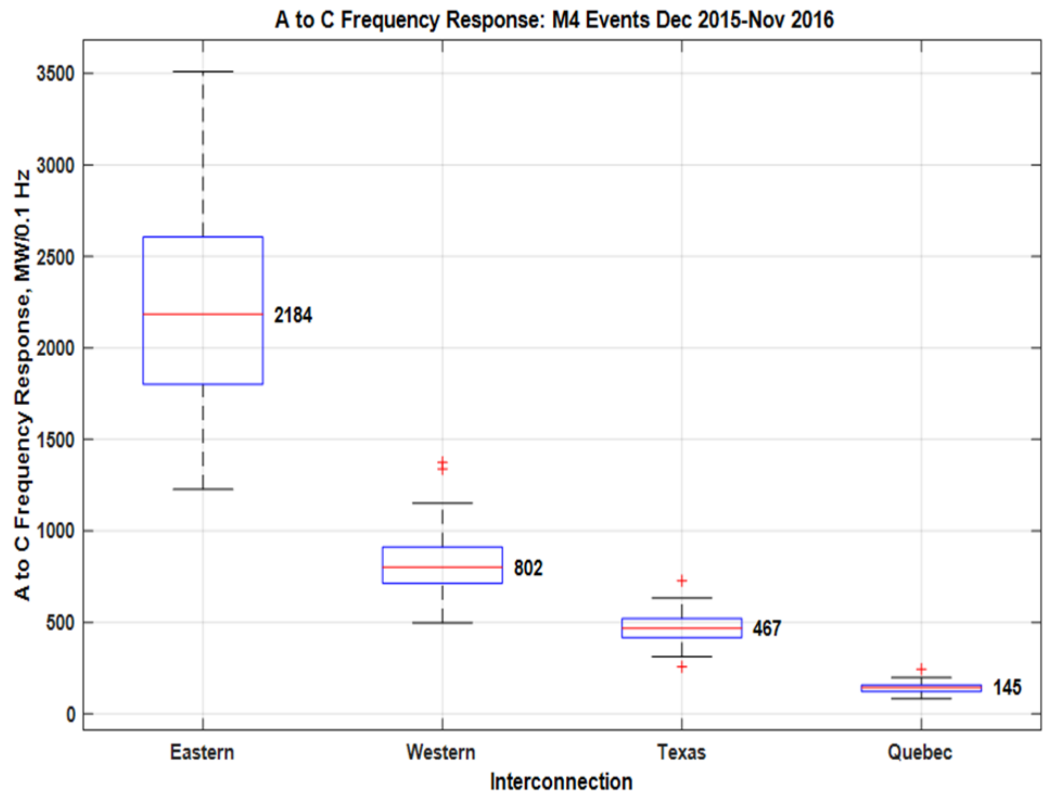
Submeasure 4.2: A to C Frequency Response

The **A to C frequency response** captures the impacts of inertial response, load response (load damping) and initial governor response[2]. This submeasure is the ratio of net MW lost to the difference between Value A and Point C frequencies.

$$\boldsymbol{Frequency\ Response\ A\ to\ C} = \frac{\boldsymbol{Generation\ (or\ Load)\ Lost\ (MW)}}{\boldsymbol{Frequency\ A - Frequency\ C}}$$

An increasing trend over time would indicate that the interconnection frequency response is improving. Figure 3 shows boxplots for Submeasure 4.2, for analyzed events that occurred between December 2015 and November 2016. The median A to C frequency in MW/0.1 Hz is listed next to the centerline (red line) of each boxplot. The table under the plot shows average generation loss in MW for the analyzed events in each interconnection.

[2] Governor response is triggered immediately after frequency exceeds a pre-set deadband; however, depending on generator technology, full governor response may require up to 30 seconds to be fully deployed.



Avg. MW Loss	938	734	601	740

Figure 3. A to C Frequency Response (Submeasure 4.2) for Analyzed Events between December 2015 and November 2016

Submeasure 4.3: C to B Ratio

The **C to B Ratio** captures the difference between the maximum frequency deviation and the settling frequency. It reflects governor responsiveness with respect to frequency nadir for the interconnection.

$$C\ to\ B\ Ratio = \frac{Frequency\ C - Frequency\ A}{Frequency\ B - Frequency\ A}$$

The C to B Ratio must be interpreted in the context of Submeasures 4.1 and 4.2. Because both Point C and Value B can vary, an increasing ratio can either indicate that frequency response is improving or degrading, and it is primarily the trend over time that is interesting. Figure 4 shows boxplots for Submeasure 4.3, for analyzed events that occurred between December 2015 and November 2016. The median C to B ratio is listed next to the centerline (red line) of each boxplot.

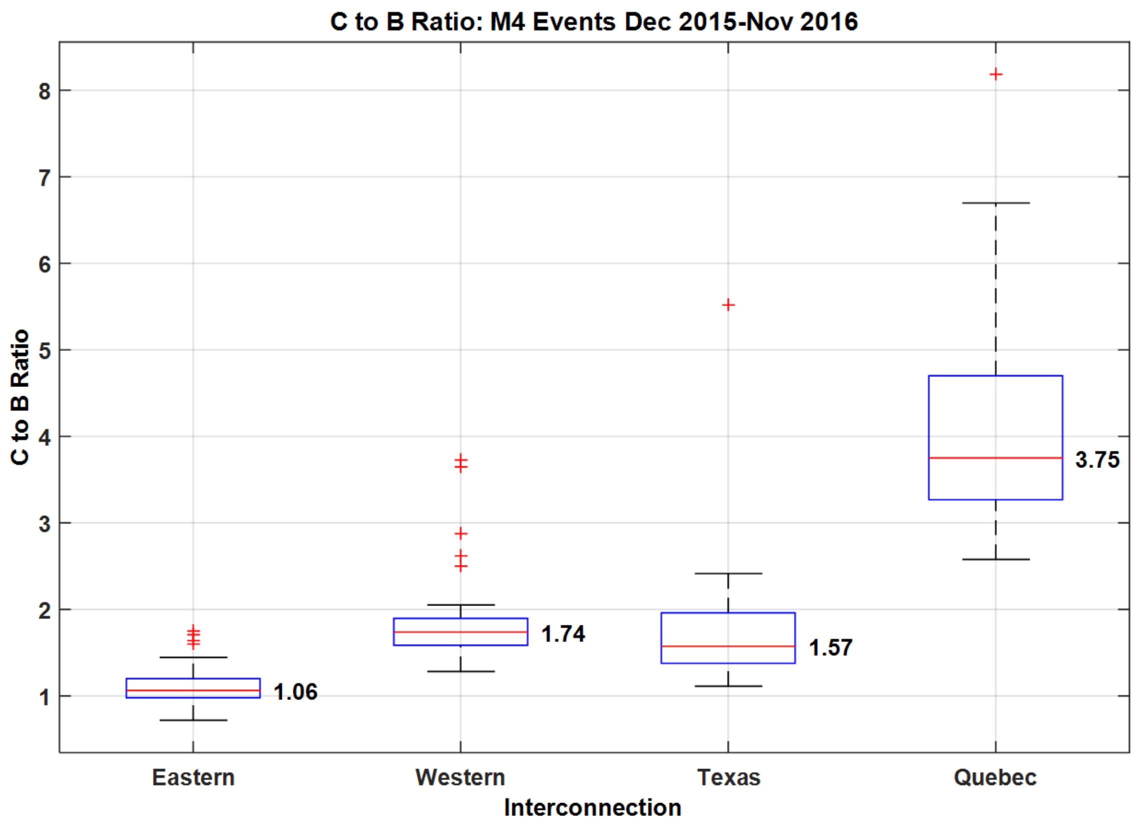


Figure 4. C to B Ratio (Submeasure 4.3) for Analyzed Events between December 2015 and November 2016

Submeasure 4.4: C' to C Ratio

When C' exists, the **C' to C Ratio** is the ratio between C' and C and potentially measures withdrawal of primary frequency response.

$$\boldsymbol{C'}\text{to } \boldsymbol{C\ Ratio} = \frac{\boldsymbol{Frequency\ C' - Frequency\ A}}{\boldsymbol{Frequency\ C - Frequency\ A}}$$

A declining trend is a possible indication of improving primary frequency response performance. Table 3 shows the subset of Metric 4 events where C' exists as well as the average frequency deviation (Hz) between Value B and Point C'.

Table 3. Metric 4 Number of Events Where C' Exists

Interconnection	Number of Events	Average f_B to $f_{C'}$ Frequency Deviation (Hz)
Eastern	41	0.006
Western	26	0.009
Texas	28	0.010
Québec	18	0.020

Figure 5 shows boxplots for Submeasure 4.4, for analyzed events that occurred between December 2015 and November 2016. The median C' to C ratio is listed next to the centerline (red line) of each boxplot.

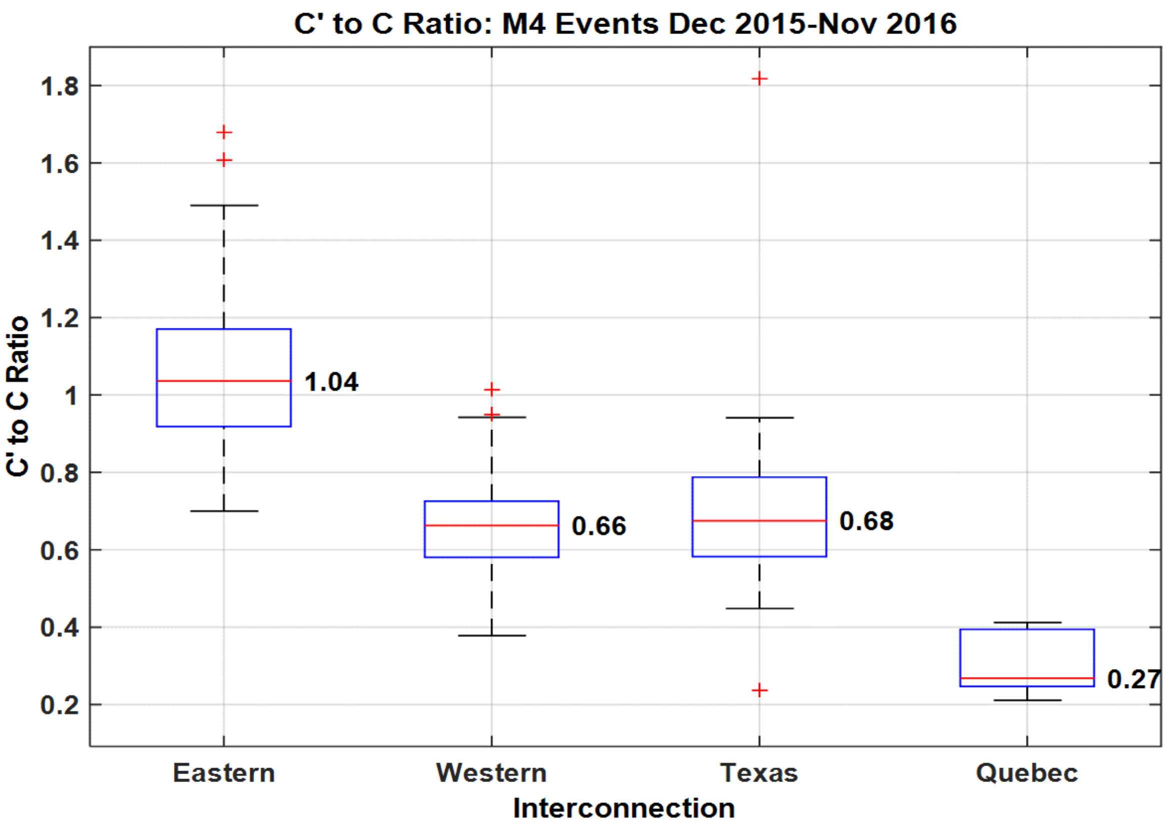


Figure 5. C' to C Ratio (Submeasure 4.4) for Analyzed Events between December 2015 and November 2016

The following time-based submeasures are used to understand the speed at which primary frequency response or governor withdrawal are occurring. As with the prior submeasures, the primary value will be from the multiyear trends that can indicate whether frequency response performance or governor withdrawal phenomena are improving or degrading.

Submeasure 4.5: Time t_0 to t_C

Time t_0 to t_c is the difference in time between the frequency nadir and initial event. This submeasure reflects the combined effects of system inertial response and initial primary frequency response (and in some interconnections, the added effects of other "fast frequency response" services).

A decreasing trend over time can reflect decreases in inertial response or the speed of frequency response due to changes in the generation and/or load resource mix. Trending this time value can also be useful for ensuring that the defined times for BAL-003-1 fit the actual event data. In addition, trending this value with respect to event size and initial frequency can help to identify how deadband settings play a role in arresting the frequency decline.

Figure 6 shows boxplots for Submeasure 4.5, for analyzed events that occurred between December 2015 and November 2016. The median time t_0 to t_c in seconds is listed next to the centerline (red line) of each boxplot.

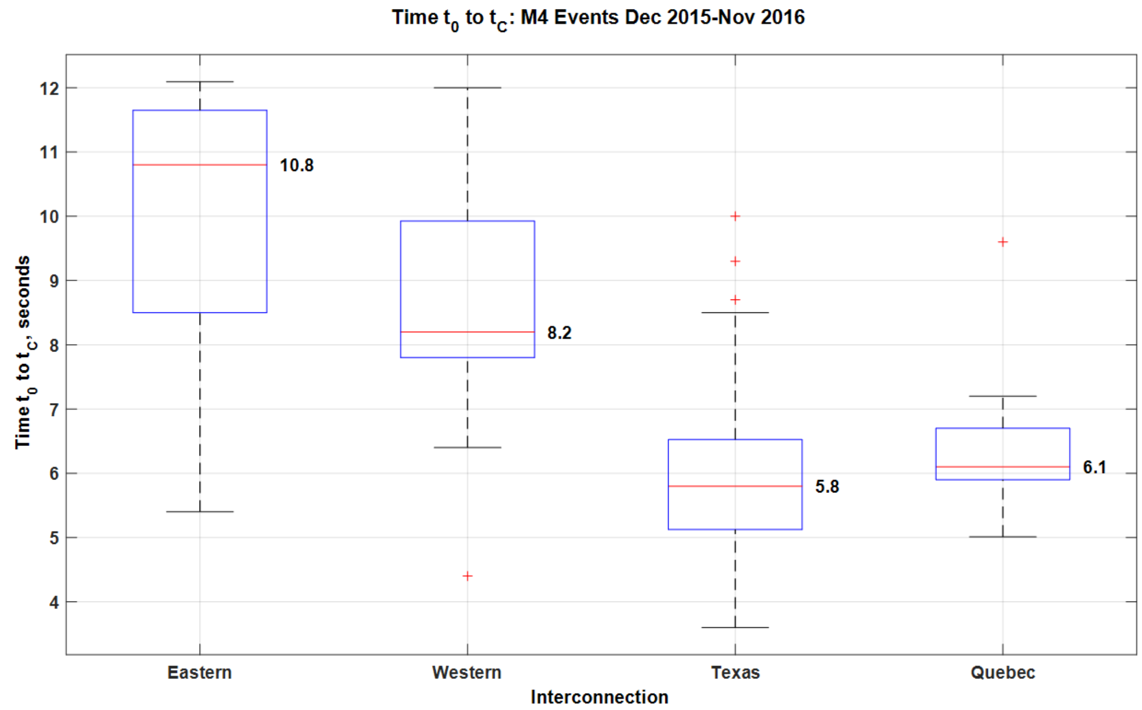


Figure 6. Time t_0 to t_c (Submeasure 4.5) for Analyzed Events between December 2015 and November 2016

Submeasure 4.6: Time t_C to $t_{C'}$

Time t_c to $t_{c'}$ to t_c is the difference in time between the governor withdrawal minimum and the initial frequency nadir. This submeasure captures the time in which governor stabilization and withdrawal occur prior to when secondary controls and load responsiveness begin to return frequency to its nominal value. Submeasure 4.6 can be derived from Submeasure 4.5 and Submeasure 4.7. Due to this redundancy, the NERC RS retired this submeasure.

Submeasure 4.7: Time t_0 to $t_{C'}$

Time t_0 to $t_{c'}$ is the difference in time between the potential governor withdrawal minimum and the initial event. This provides a comprehensive picture of the overall time in which frequency declines and continues to fall after the initiating event. While C' should be mitigated and eliminated entirely, the time between the initial event and absolute minimum should be minimized.

Figure 7 shows boxplots for Submeasure 4.7 for analyzed events that occurred between December 2015 and November 2016. The median time t_0 to $t_{C'}$ in seconds is listed next to the centerline (red line) of each boxplot.

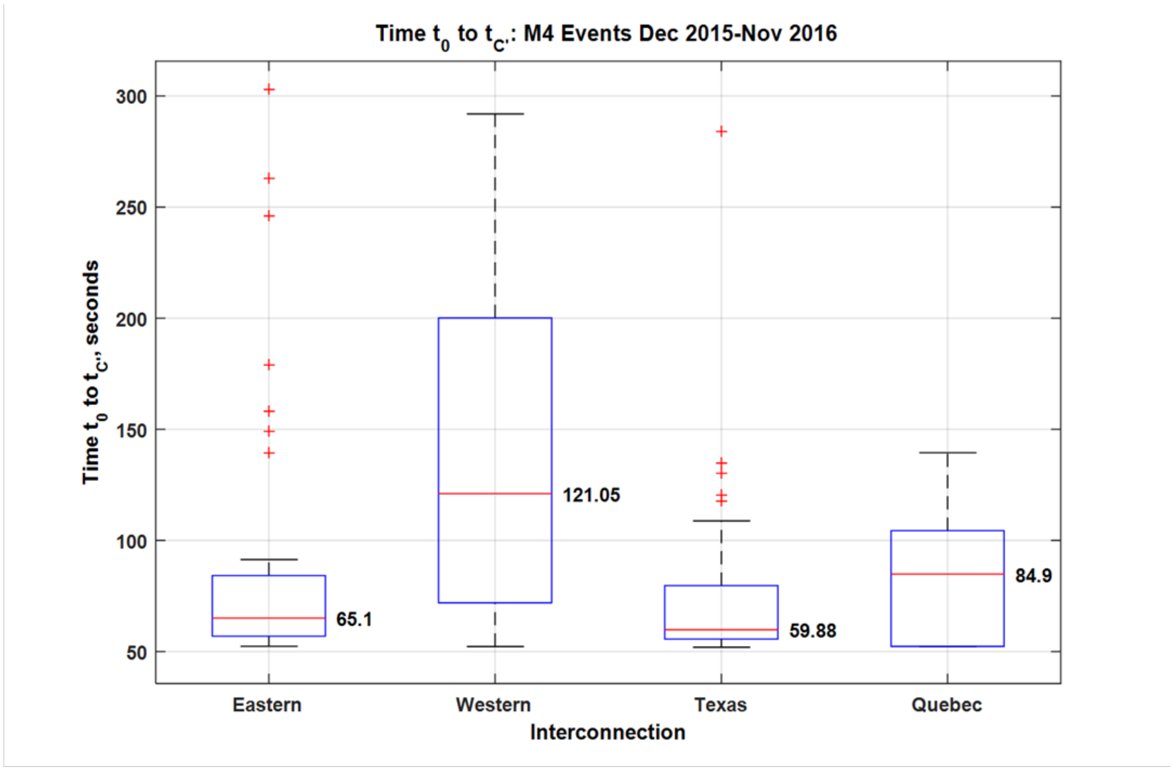


Figure 7. Time t_0 to $t_{C'}$ (Submeasure 4.7) for Analyzed Events between December 2015 and November 2016

The NERC RS will continue to enhance methods to analyze and report the findings and trends based on actual events. Proposed enhancements include evaluating:

- the maximum frequency excursion after the start of an event (Point C_n) [3] ;
- the frequency margin from C_n to the first step in underfrequency load shedding relative to each interconnection;
- the relationship and timing associated with C_n and C'.

[3] C_n is defined as the lowest frequency from the start of the event up to 180 seconds

Measure 1: Synchronous Inertia Response

For historical trending of SIR (Measure 1), a process was established for conducting synchronous inertia calculations for each interconnection. System inertia depends on the inertial constant (referred to as 'H') and MVA base[4] of the generators that are online and synchronized to the grid at a given point in time. Therefore, for each historical time step, the total SIR for the interconnection can be calculated as a sum of H*MVA base for all online synchronous generators. This data, along with some supporting information, is now being collected and provided to the NERC RS on a quarterly basis. The data varies slightly depending on the interconnection as follows:

- The Texas Interconnection and Quebec Interconnection provide total system inertia, system load, power production from non-synchronous generation, and HVDC exports/imports. The data is provided with 4 second resolution.
- For the Western Interconnection, Peak RC provides total system inertia, system load, power production from non-synchronous generation, and HVDC exports/imports. The data is provided with 1 minute resolution.
- For the Eastern Interconnection, MISO has been providing total system inertia and system load. The data is provided with 15 minute resolution. This data is a part of ongoing project in collaboration with Eastern Interconnection. In 2018, the Eastern Interconnect Data Sharing Network (EIDSN) will provide the data.

A platform is being developed to facilitate the direct submission of the data to NERC using PI Historian software. The NERC RS will analyze the data and provide reports on trends each year. As an example, Figure 9 shows inertia trends in ERCOT from January 2013 to September 2017. Similar boxplots will be produced for other interconnections when sufficient amounts of data are collected.

[4] The inertial constant is calculated based on the machine size, weight, nominal speed and converted to seconds using chosen MVA base. MVA base is not necessarily equal to generator MVA nameplate rating.

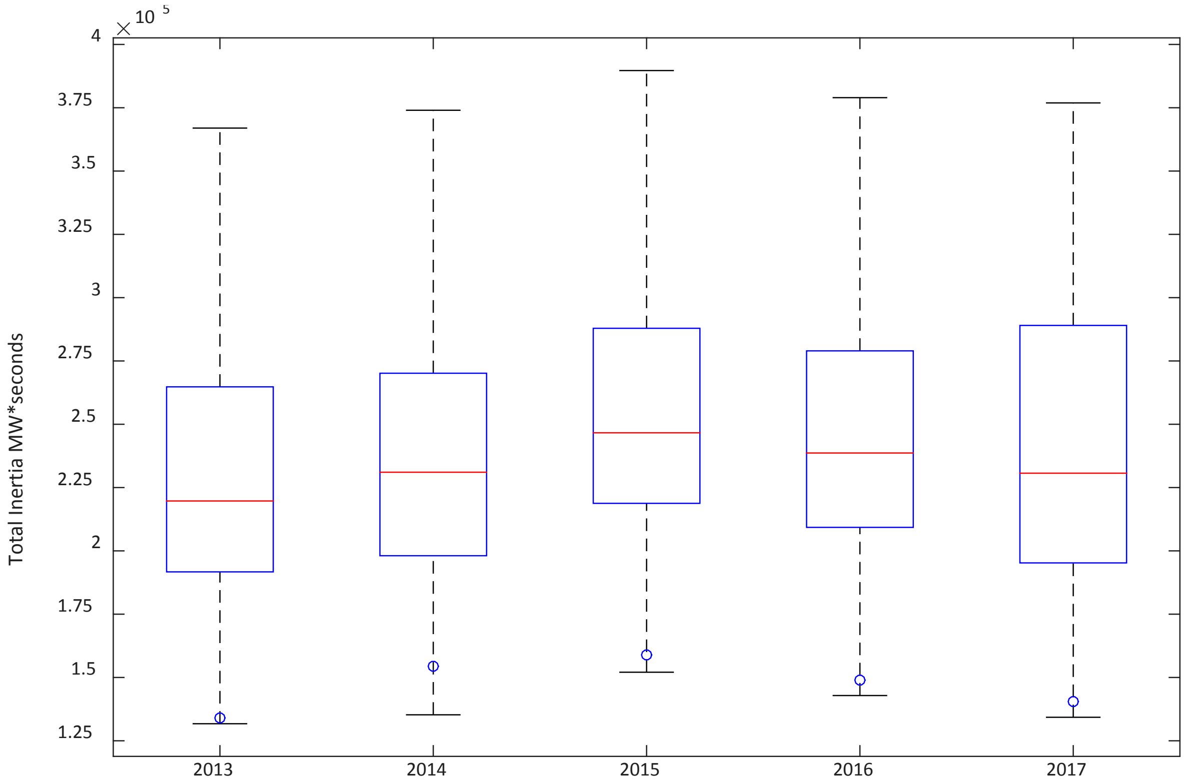


Figure 8. Boxplot of the system inertia in ERCOT 2013-2017[5]

[5] Blue dots correspond to actual system inertia during the maximum wind penetration times in each year, when the highest portion of load was supplied by wind generation.

Measure 2: Initial Rate of Change of Frequency after Large Contingency

Measure 2 is the initial Rate of Change of Frequency (RoCoF) after a large generator trip event and is measured in Hz/s. This is an indirect measure of interconnection inertia at the time of the event. RoCoF can be calculated for each interconnection from the lowest SIR value in each year and the megawatt (MW) size of the largest contingency event for the interconnection. The Resource Contingency Criteria (RCC) as defined in the BAL-003 Standard is used as the largest contingency event.

The RoCoF and the load shedding settings for the interconnection can be used to calculate the shortest available time during which sufficient frequency response must be provided to the interconnection in order to establish the frequency nadir and avoid underfrequency load shedding. In reality, a component of RoCoF is the load damping coefficient for each interconnection. The load damping coefficient for each interconnection is being further refined by the NERC RS.

If the time between the event and the frequency nadir is becoming smaller (as suggested by the RoCoF and more precisely indicated by Submeasure 4.5), there may be value in the interconnection obtaining faster frequency response from generators and loads.

As with SIR, RoCoF trends will be analyzed by the NERC RS each year. As an example, Table 2 shows the largest RoCoF for each interconnection for the first two quarters of 2017 calculated without consideration of load damping (i.e., using pessimistic assumptions).

Table 4. RoCoF by Interconnection - 2017 Q1 and Q2

$$RoCoF = \Delta P_{MW}/(2*(KE_{min}-KE_{RCC}))*60 \quad [Hz/s]$$

2Q 2017						
Date Time	Min Inertia MVA-sec	Interconnection Load MW	RCC MW	RCC Inertia MVA-sec	RoCoF (mHz/sec)	Interconnection
5/7/2017 2:43	1,038,756	215,222	4,500	16,898	132	Eastern
4/9/2017 19:19	471,903	86,183	2,626	12,000	171	Western
4/24/2017 7:00	136,648	25,661	2,750	12,000	662	Texas
5/26/2017 4:30	63,460	14,710	1,430	7,000	760	Quebec
1Q 2017						
Date Time	Min Inertia MVA-sec	Interconnection Load MW	RCC MW	RCC Inertia MVA-sec	RoCoF (mHz/sec)	Interconnection
3/25/2017 3:11	1,076,436	226,908	4,500	16,898	127	Eastern
3/25/2017 11:49	486,259	80,782	2,626	12,000	166	Western
2/10/2017 7:00	134,209	29,515	2,750	12,000	675	Texas
3/1/2017 1:30	91,100	20,670	1,430	7,000	510	Quebec