NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Introduction to Frequency Considerations

Utility Variable-Generation Integration Group
Mark Ahlstrom, Troy Blalock, Julia Matevosjana

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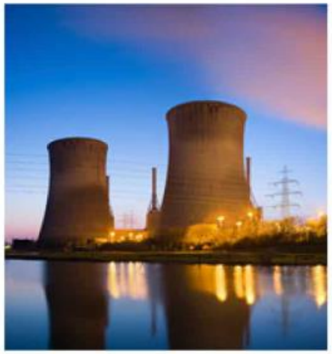
UVIG

RELIABILITY | ACCOUNTABILITY

Background

- Frequency response may change due to changes in the characteristics of our generators and loads
- The goal is to understand these changes, monitor historical performance/trends, and produce future projections for all four interconnections
  - If and when the trends may approach a level of concern, it is prudent to have time to plan and implement necessary changes and adjustments
- Working to streamline the process and provide results in the NERC State of Reliability Report (historical) and Long Term Reliability Assessment Report (projecting forward)

Frequency after a Disturbance Event

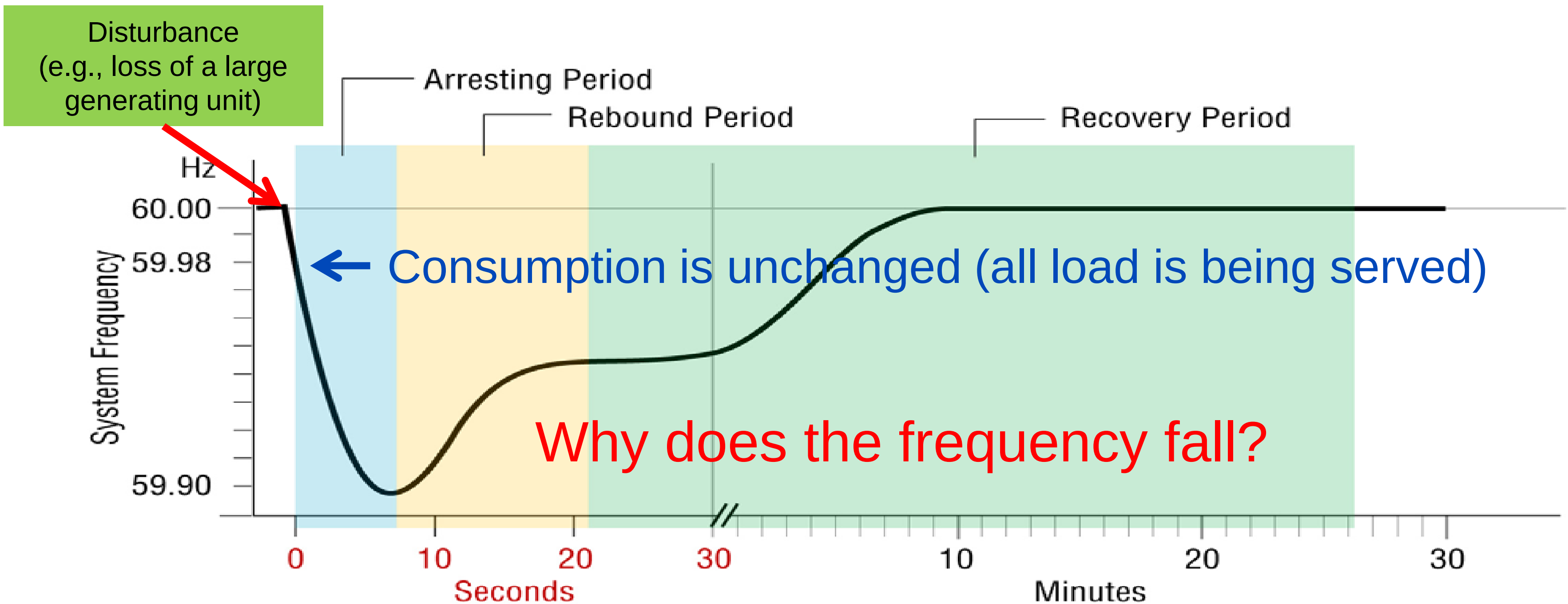


Figure from J. Eto, LBNL,
https://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf

Synchronous Generators

- Mechanical torque goes in (from the energy source - “prime mover”)

- Electrical torque is pulled out (the electrical power to the grid)

- When starting up, energy is applied to bring the generator up to speed and then it is synchronized (electro-mechanically coupled) with the electrical grid

- Thereafter, the plant controls try to maintain a “torque in = torque out” balance to generate the desired power output level

Synchronous Inertial Response Example

1) We are operating normally and serving load of 10,000 MW
2) We lose a 500 MW generator
3) We are still serving 10,000 MW of load, but are now pulling 10,000 MW from generators that were previously generating 9,500 MW
4) The extra 500 MW is withdrawn from the kinetic energy of the synchronous generators (the "inertia" of the rotating machines)
5) As kinetic energy is reduced, rotational speed is reduced

Frequency falls because the synchronous rotating generators slow down as we cannibalize their kinetic energy to maintain power balance

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Misconceptions about Synchronous Inertial Response (SIR)

- ***"SIR stops the frequency from falling"***
  - No, frequency will continue to fall without other actions
  - SIR only sets the initial rate at which the frequency falls
- ***"Coal plants are the best source of SIR"***
  - Combined cycle gas plants often provide more SIR on a nameplate basis (i.e., have a higher "inertial constant")
  - Synchronous motors and synchronous condensers (which are essentially synchronous generators without a fuel source) also provide SIR
- ***"The amount of SIR depends on the plant's current output level"***
  - No, the plant must be online and synchronized to the grid, but then the SIR contribution is the same regardless of the output level

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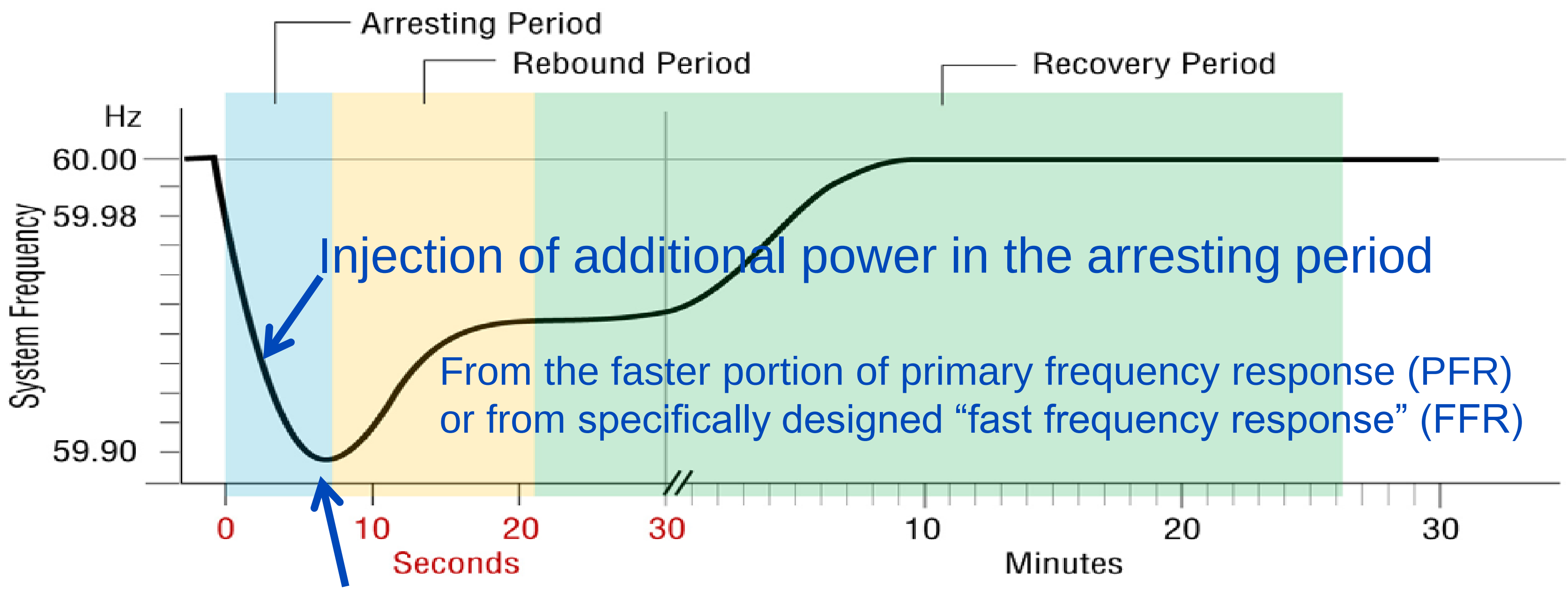
What Stops the Frequency from Falling?



Injection of additional power in the arresting period

From the faster portion of primary frequency response (PFR) or from specifically designed “fast frequency response” (FFR)

Goal is to establish the “nadir” (minimum frequency point) before reaching under frequency load shedding (UFLS)

Primary Frequency Response (PFR)

- **NERC recommended setting for generators:**
  - Deadband of 0.036 Hz or less
  - Then, a linear response of 5% (“droop”)
- **5% droop means that for a 5% change in frequency, power output changes by 100%**
  - 4% droop is MORE aggressive than 5% droop
- **Traditionally, the deadband is justified to:**
  - Avoid excessive governor action
  - Avoid interfering with regulation, dispatch and time correction operator control actions
  - Approximate the inherent delays and hysteresis of mechanical and physical equipment

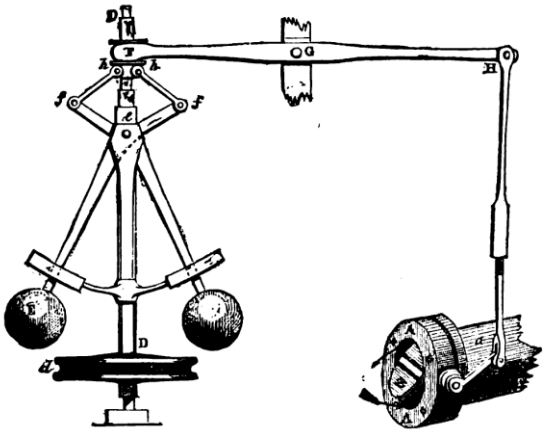


FIG. 4.—*Governor and Throttle-Valve.*

Centrifugal (“flyball”) governor invented in 1788 by James Watt to control his steam engine

PFR versus Frequency Regulation

- **PFR is automatic and proportional (outside of the deadband)**
  - Proportional response does not bring frequency back to 60 Hz

- **Frequency regulation follows a signal every 3-4 seconds**
  - Generally, regulation is reserved capacity and receives compensation

- **Interaction between frequency response and regulation**
  - Tighter deadband and faster frequency response reduces the need for regulation

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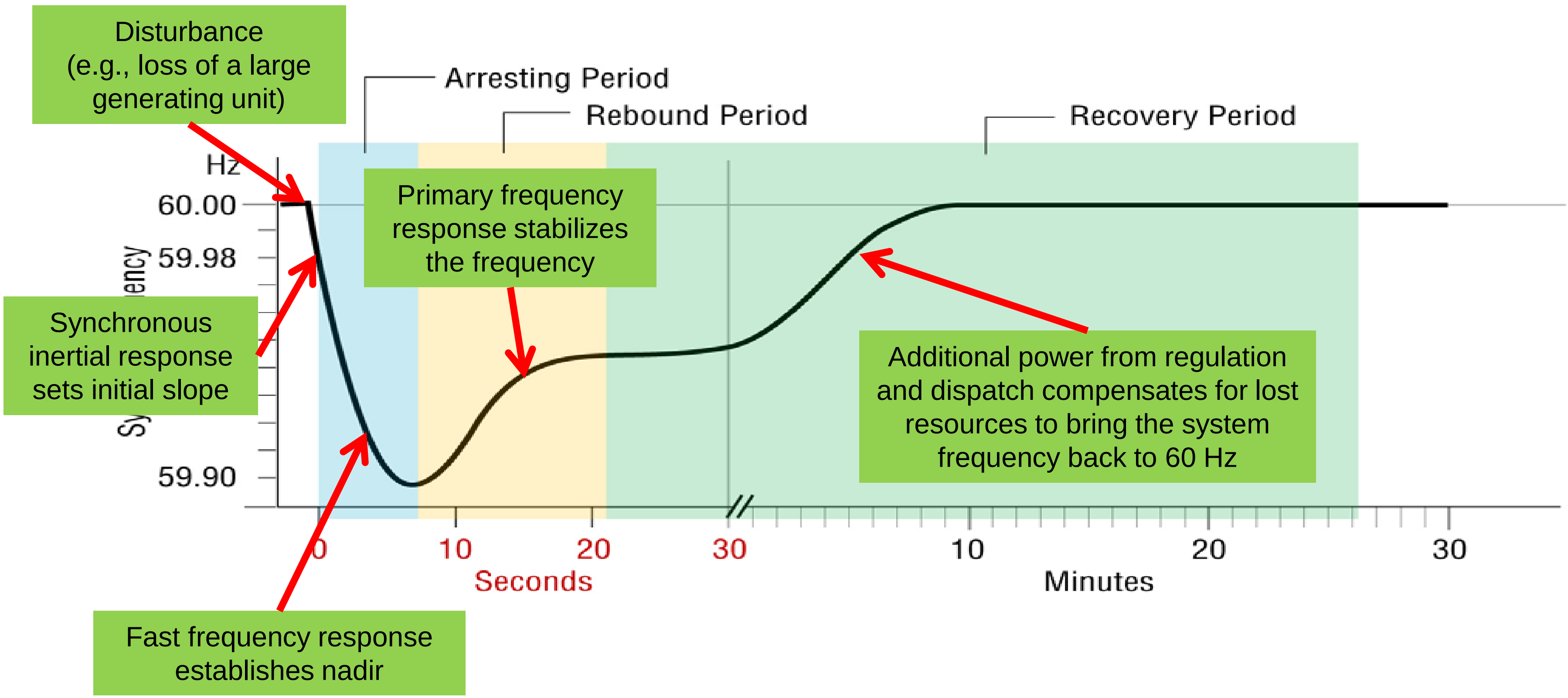
Putting it all Together: Frequency Response to an Event



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Frequency as Communications

- **Frequency is global (for the entire interconnection)**

- **Voltage is a critical parameter, but unlike frequency, voltage is local**

- **Frequency is being used as a convenient form of communication**
  - Frequency is really telling us the speed of the synchronous generators
  - Frequency becomes a proxy for the overall balance between generation and load
  - All generators see the frequency, so they can use it to detect a disturbance

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Differences Between Generator Types

- **Synchronous generators**
  - Electro-mechanically coupled to the grid
  - Torque difference → changes the rotational speed (which changes frequency)
  - Can provide very large overload currents for a few seconds during a fault
    - -- Today's protection schemes often depend on these short circuit currents

- **Today's power electronics**
  - Examples: inverter-based resources like wind, solar, battery storage
  - Electronically coupled to the grid
  - Current difference → changes the voltage
  - Typically not oversized to provide large amounts of additional fault current
  - Programmed to follow grid frequency
  - They could be engineered and programmed to be "grid forming" and provide other features, but they typically aren't today…

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ERSWG Measures

- Essential Reliability Services Task Force in the final report 2015 recommended data collection and trending for:
  - **Measure 1:** Interconnection level inertia
  - **Measure 2:** Frequency deviation in the first 0.5 seconds after Resource Contingency Protection Criteria (RCPC)[1] at minimum inertia level.

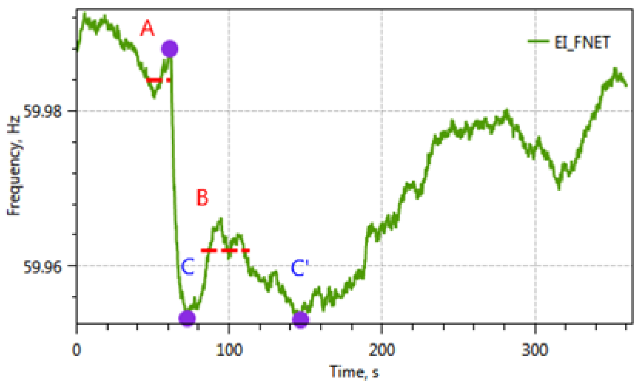
    This measure captures only the impact of system inertia on initial frequency rate of change after a large event. The measure is meant to provide early on indication if changes are needed to existing frequency response mechanisms.
  - **Measure 3:** BA level inertia (Under evaluation)
  - **Measure 4:** Frequency Performance after Large Contingency

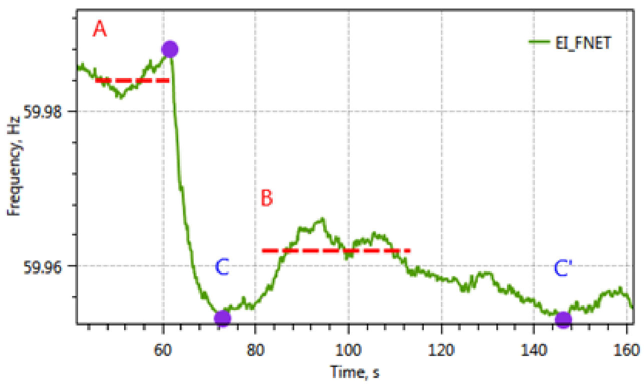
[1] RCPCs are defined in the NERC Frequency Response Initiative Report – October 2012

Measure 4: Frequency Response

EI_20170108_082021

Event ID	EI_20170108_082021
Event Description	Amos 3
UTC Time	01/08/2017 08:20:21
Local Time	01/08/2017 03:20:21
Time Zone	Eastern Standard Time
M4 Flag	Yes
BAL003 Flag	No
MW Loss	998
Value A	59.984
Value B	59.962
Point C	59.9532
Time of C	11.4
Point C'	59.953
Time of C'	85
A-B [mHz]	22
A-C [mHz]	31
FRM_B [MW/0.1Hz]	4536
FRM_C [MW/0.1Hz]	3240



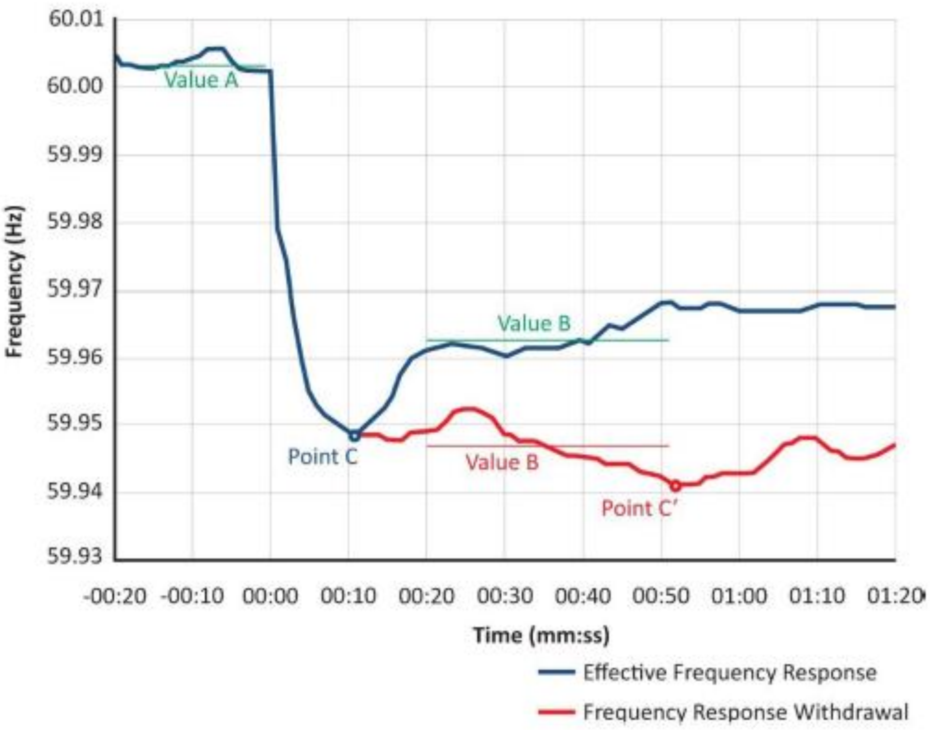


More Granular Trending

- A-B frequency response
  - Conventional f response
- A-C frequency response
  - Inertial, load & initial governor response
- C to B ratio
  - Governor responsiveness
- C' to C ratio
  - Governor withdrawal
- Time based measures
  - t_c-t_0
  - $t_{c'}$-t_0
- Additional work evaluating C - UFLS

Frequency Response

This figure illustrates a frequency deviation due to a loss of generation resource and the methodology for calculating frequency response. ***The event starts at time t0****.* ***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 and Value B is the average from t+20 to t+52 seconds. Point C' occurs when the frequency after 52 seconds falls below either the Point C (12 seconds) or average Value B (20 – 52 seconds).***



The difference between Value A and Value B is the change in frequency used for calculating primary frequency response. Frequency response is calculated as the ratio of the megawatts lost when a resource trips and the frequency deviation. For convenience, frequency response is expressed in this report as an absolute value. A large absolute value of frequency response, measured in MW/0.1Hz, is better than a small value.

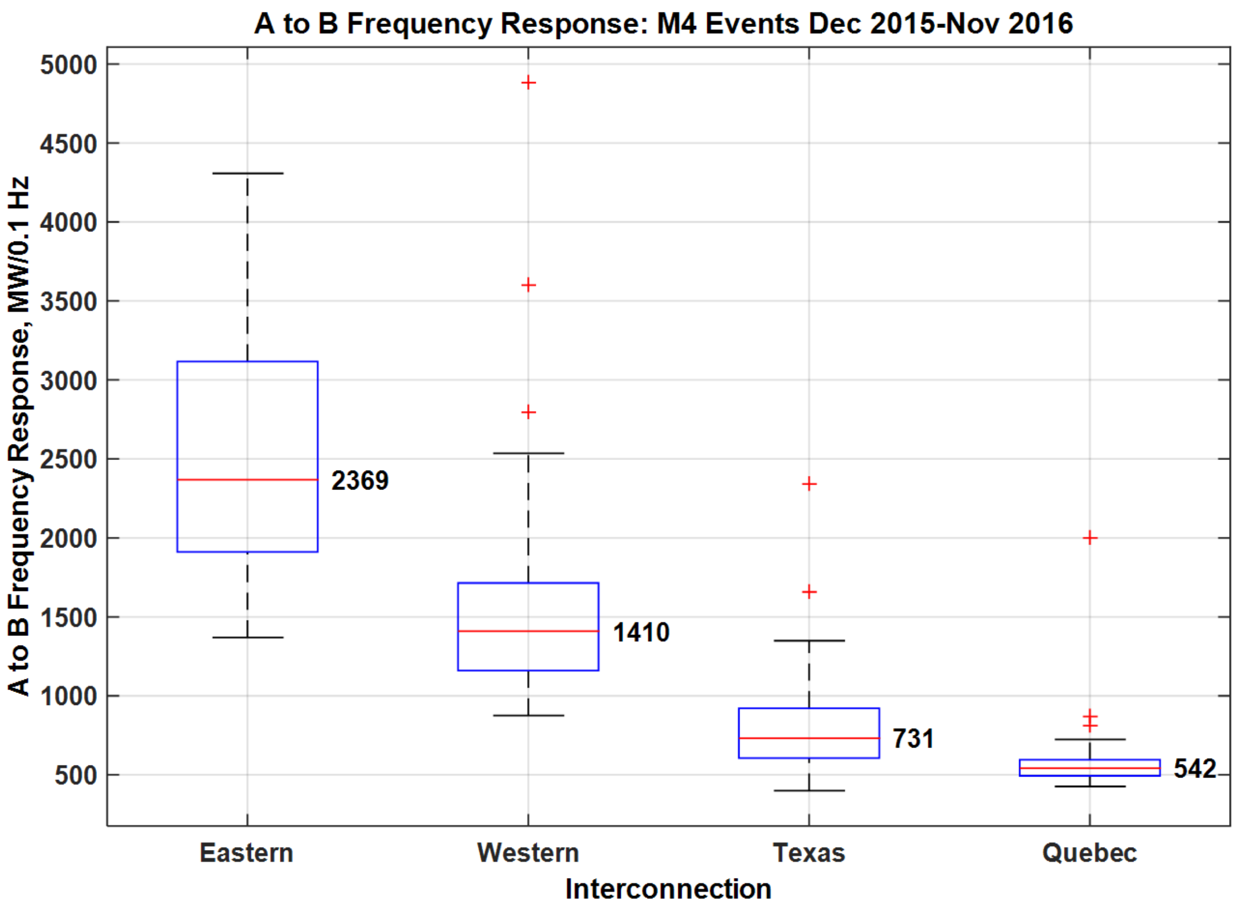
Measure 4.1 : A to B Frequency Response

A to B frequency response captures the effectiveness of primary frequency response in stabilizing frequency following a large frequency excursion. This Measure is the conventional means of calculating frequency response as the ratio of net MW lost to the difference between Point A and Point B frequency values.

$$\boldsymbol{Frequency\ ResponseA}_{\boldsymbol{toB}} = \frac{\boldsymbol{Generation\ (or\ Load)\ \ Lost\ (MW)}}{\boldsymbol{Frequency_A - FrequencyB}}$$

The A to B frequency response measures primary frequency response for each interconnection so that adequate frequency support is provided to arrest and stabilize frequency during large frequency events. An increasing trend over time indicates that frequency response is improving in that interconnection. Frequency response is measured in (absolute value) MW/0.1Hz. Histogram distributions reflect the variability of interconnection response to individual events.

Measure 4.1 : A to B Frequency Response



Avg. MW Loss	938	734	601	740

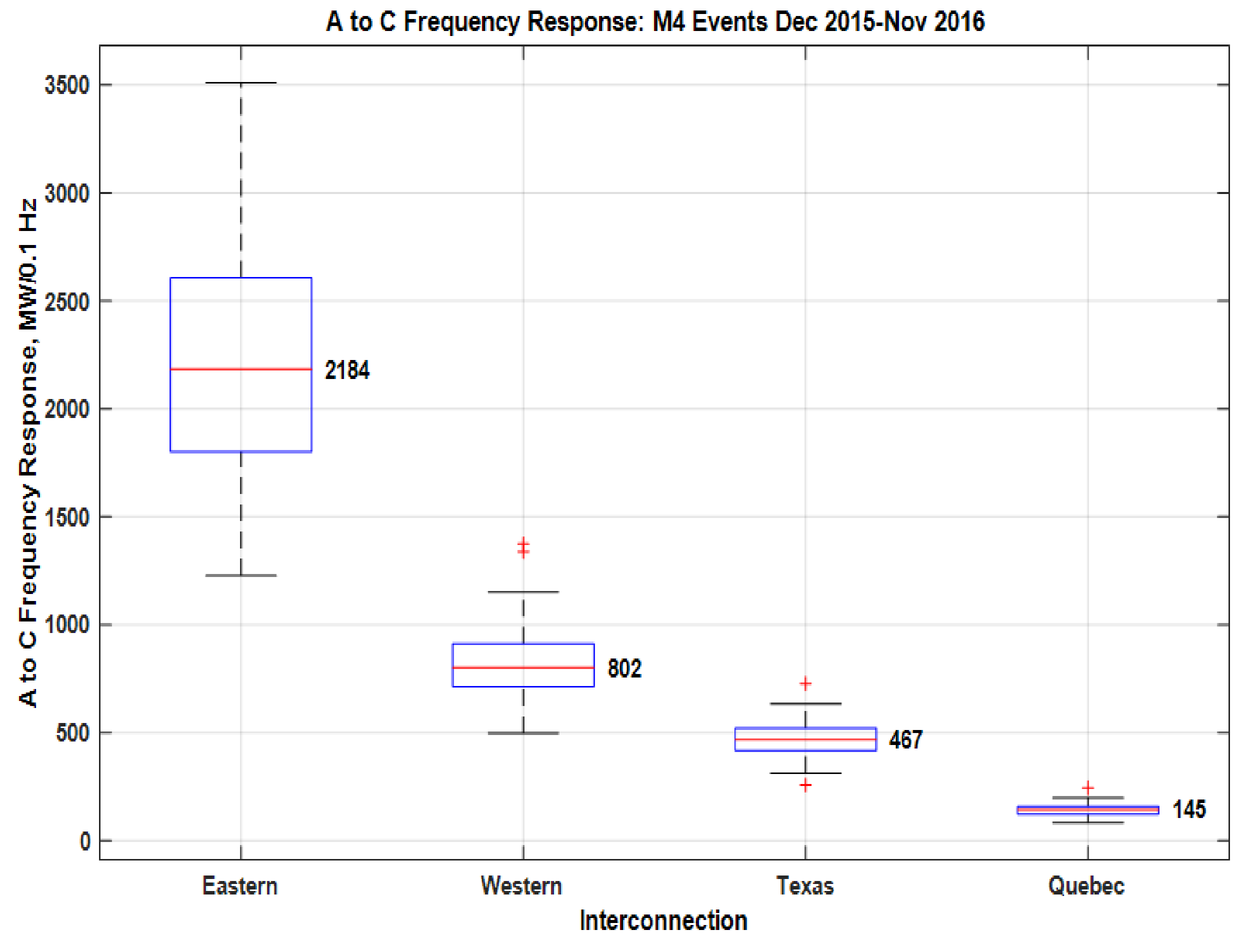
Measure 4.2 : A to C Frequency Response

A to C frequency response captures the impacts of inertial response, load response (load damping) and initial governor response (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). This Measure is calculated as the ration of net megawatts lost to the difference between Point A and Point C frequency values.

$$\boldsymbol{Frequency\ ResponseAC} = \frac{\boldsymbol{Generation\ (or\ Load)\ \ Lost\ (MW)}}{\boldsymbol{Frequency_A - FrequencyC}}$$

The A to C frequency response measure identifies year over year trends that could be due to changes in generation mix and load characteristics. An increasing trend over time indicates that frequency response is improving in that interconnection. Frequency response is measured in (absolute value) MW/0.1Hz. Histogram distributions reflect the variability of interconnection response to individual events.

Measure 4.2 : A to C Frequency Response



Avg. MW Loss	938	734	601	740

Measure 4.3 : C to B Ratio

C to B ratio captures the difference between maximum frequency deviation and setting frequency. The C to B ratio is related to governor responsiveness with respect to frequency nadir and the interconnection capability to arrest and stabilize system frequency.

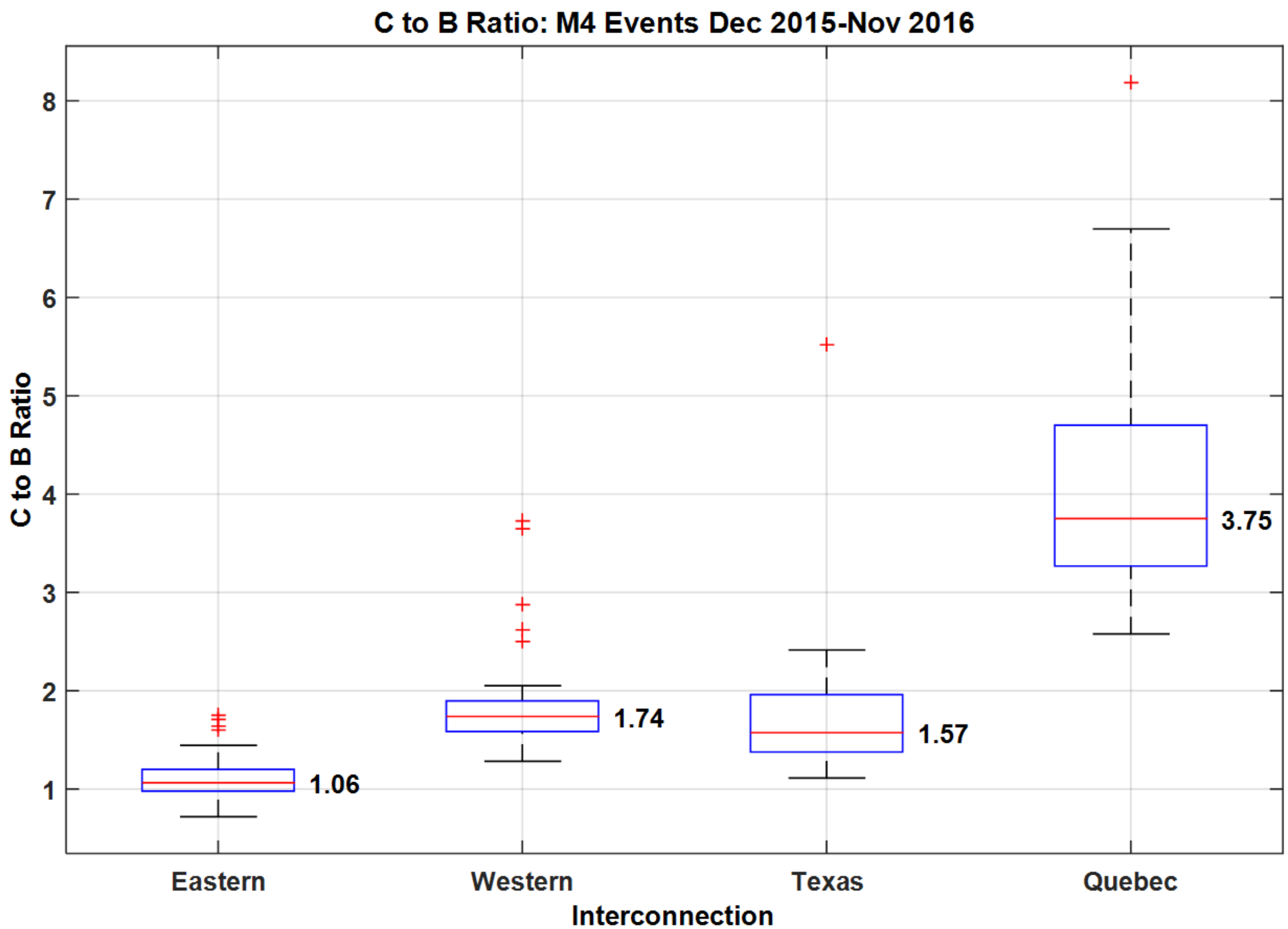
$$C\!:B\ Ratio\ = \frac{Frequency_C\ - FrequencyA}{Frequency_B\ - FrequencyA}$$

The C to B ratio measures primary frequency response trends for each interconnection so that adequate frequency support is provided to arrest and stabilize frequency during large frequency events.

$$Note\ that\ the\ ratio\ \frac{FRM\ B}{FRM\ C} = \frac{C-A}{B-A} = C\ to\ B\ Ratio$$

The C to B ratio should be considered in coordination with Measures 4.1 and 4.2. This measures annual trends between maximum frequency deviation and settling frequency. An increasing ratio can either indicates that frequency response is improving or decreasing in that interconnection as Point C and Point B vary.

Measure 4.3 : C to B Ratio



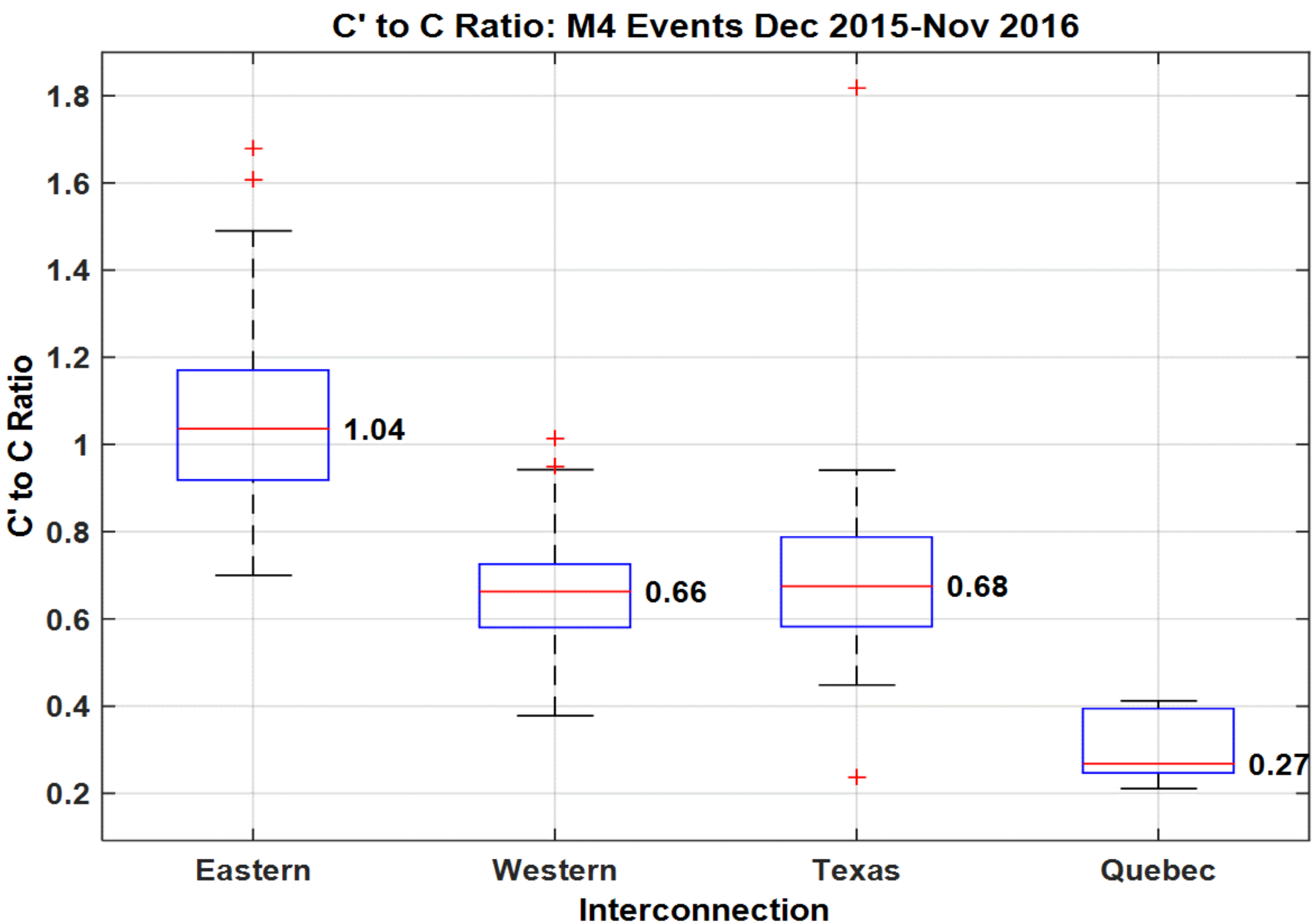
Measure 4.4 : C' to C Ratio

C' to C ratio is the ratio between the absolute frequency minimum (Point C') caused by governor withdrawal and the initial nadir (Point C).

$$\boldsymbol{C' : C\ Ratio\ = \frac{Frequency_{C'}\ \_\ Frequency_{A}}{Frequency_{C}\ -FrequencyA}}$$

This metric measures withdrawal of primary frequency response. A response greater than 1.0 indicates withdrawal. A declining trend is an indication of improving primary frequency response.

Measure 4.4 : C’ to C Ratio

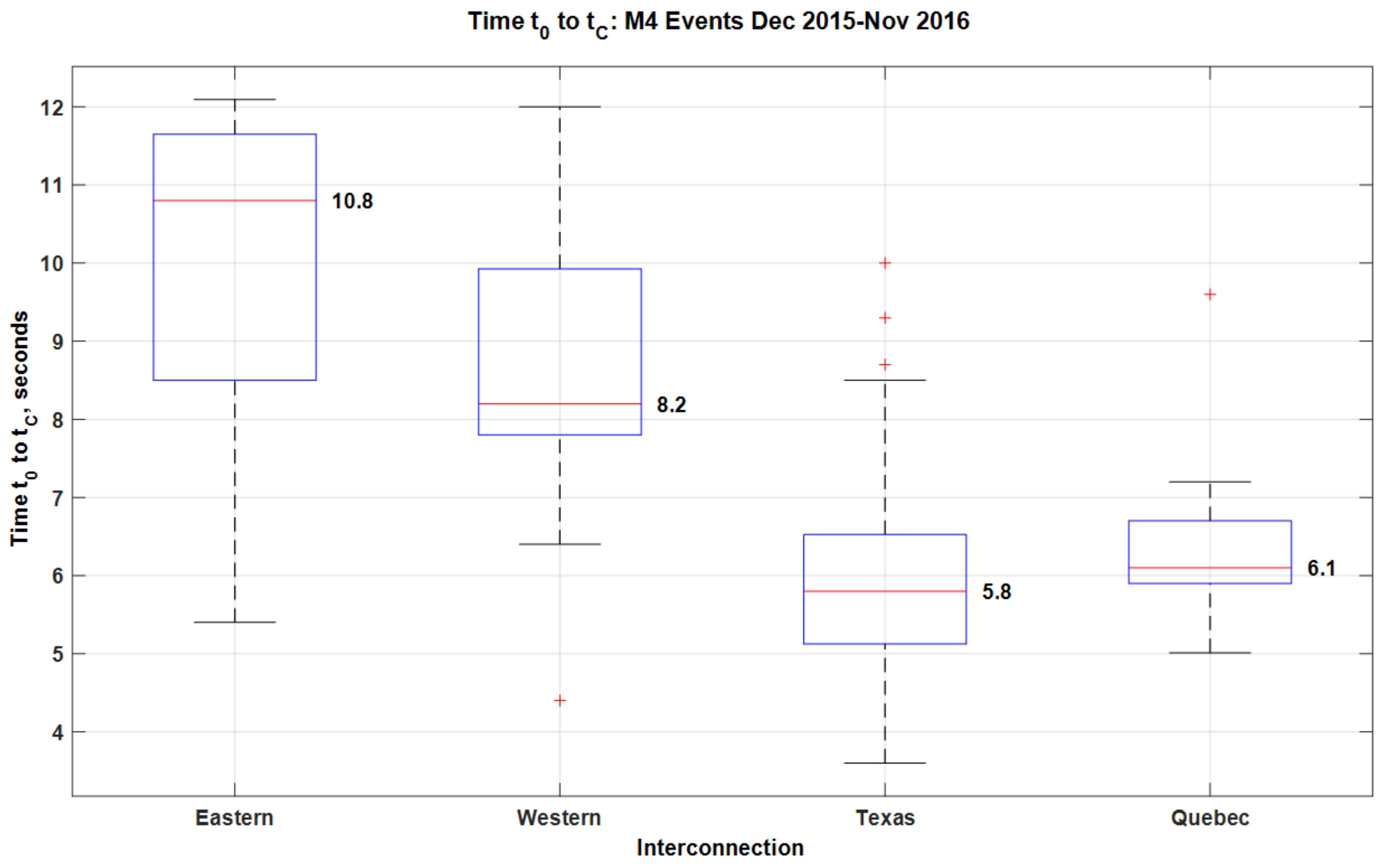


Measure 4.5 : tc – t0

t_c-t_0 is the difference in time between the frequency nadir and initial event. It captures the time in which system inertia and governor response arrest declining frequency to its minimum level. Trending this time difference can be useful for ensuring that the defined times for BAL-003-1 fit the actual event data. In addition, trending this with respect to event size and initial frequency can help identify how deadband settings play a role in arresting the frequency decline.

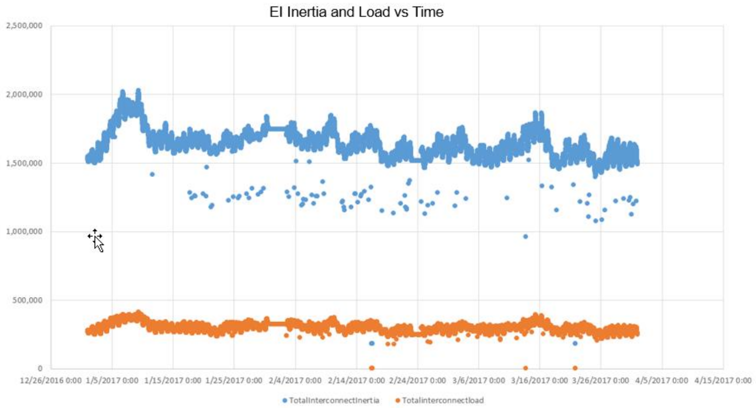
The tc-t0 measure identifies annual trends of changes in time from Cn and initial event. A decreasing trend over time can reflect the changes in inertia caused by changes in generation and load resource mix.

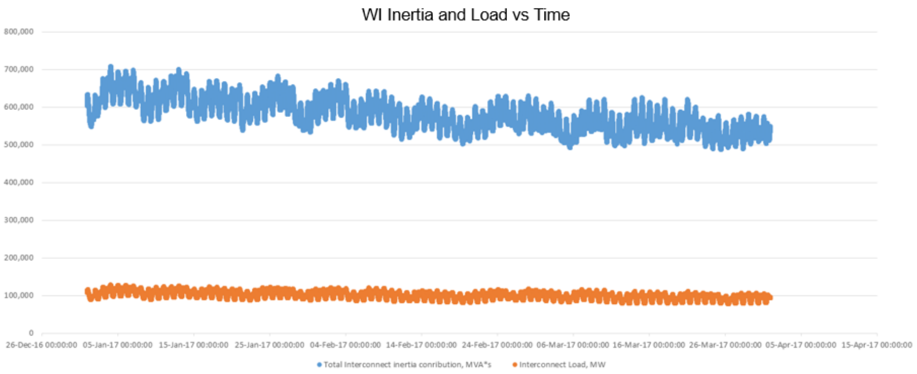
Measure 4.5 : tc –t0

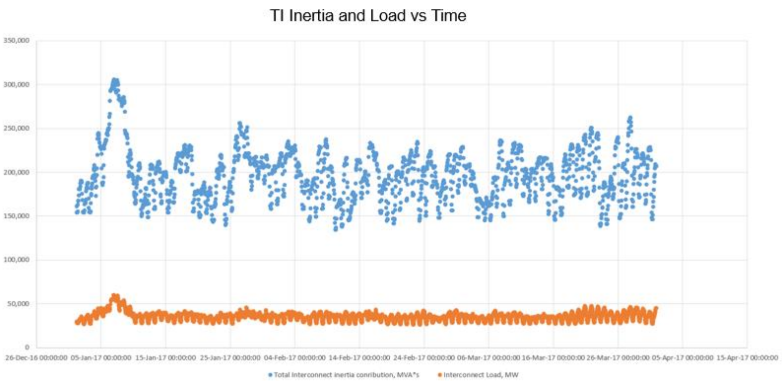


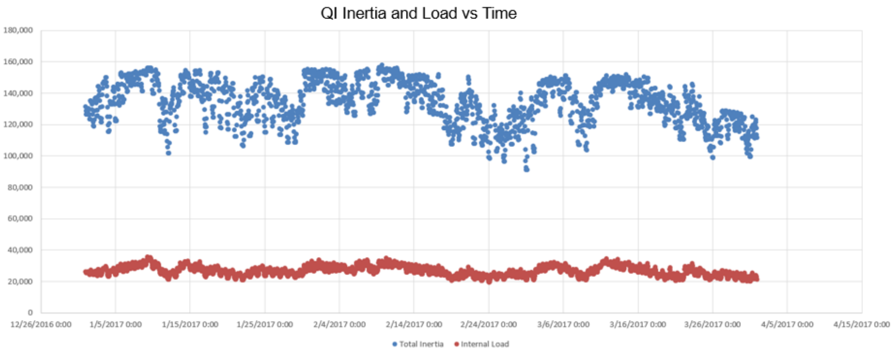
Measure 1 : Interconnection Synchronous Inertia

- All four Interconnection have providing data since June 2016









ERS Measure M1 Data

Data Format

Timestamp

Total Interconnect Inertia, MVA*s

Total Interconnect Load, MW

Production from Non-Synchronous Generation

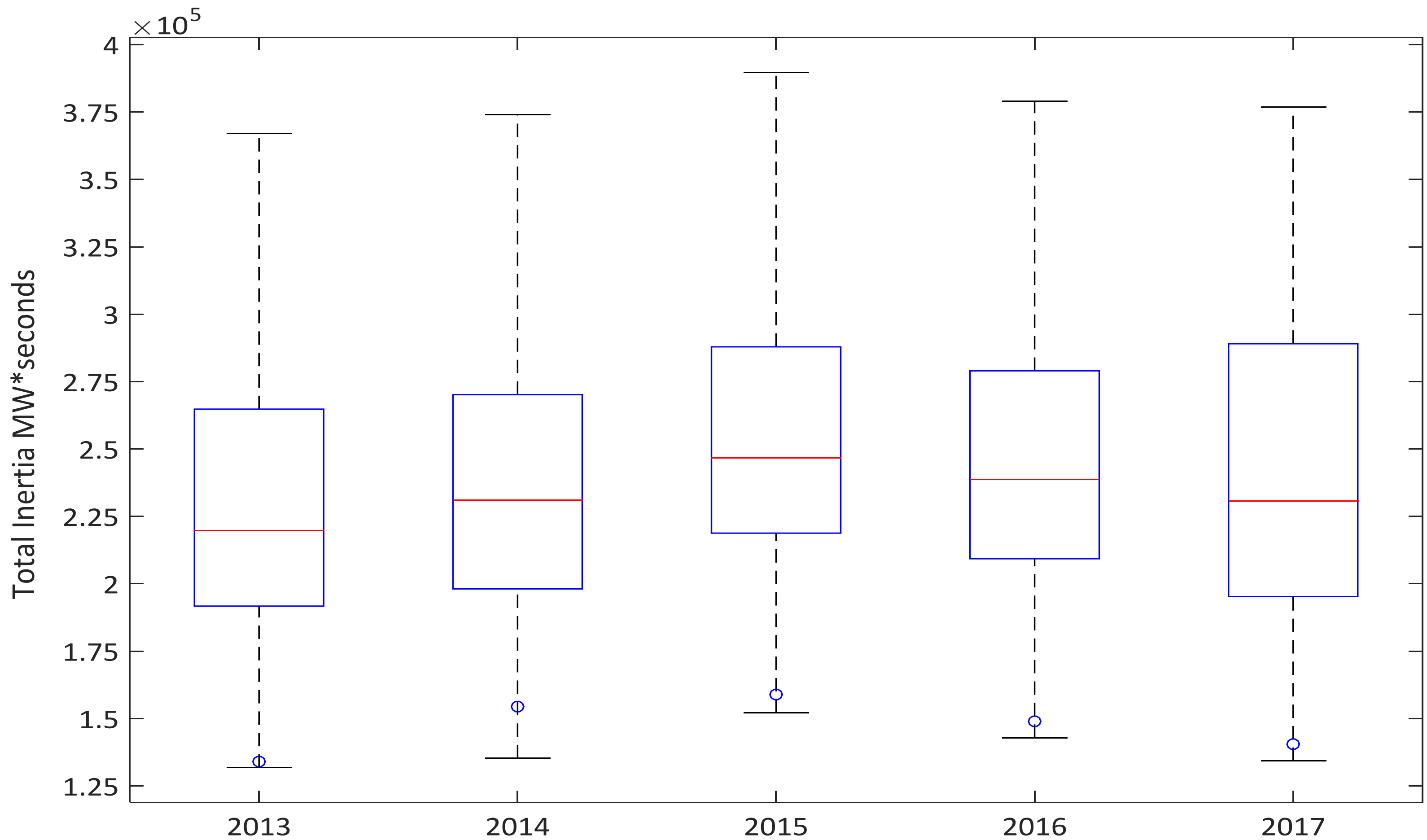
DC Exports/Imports

EI data is being provided every 15 min

WI data is being provided every 1 min

EROCT and Quebec every 4 sec

ERCOT Boxplot of Inertia 4 years



ERS Measure M2: Background

- Calculated for each interconnection from the lowest SIR value in a year and the size of the largest contingency event for the interconnection (the Resource Contingency Criteria as defined in the BAL-003 Standard).

- **The RoCoF value and the load shedding settings for the interconnection can be used to calculate the time during which sufficient frequency response must be provided to the interconnection.**

- A component of RoCoF is the load dampening value for each interconnection. The load dampening value for each interconnection is being further refined by the NERC Resources Subcommittee.

Measure 2: ROCOF Calculations

Measure 2 for all interconnections for 2017 Q1 and Q2 2017

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

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

- **RoCoF is a value is a worst case evaluation.**
  - **Lowest Inertia**
  - **Largest contingency**
  - **No load effect**
- Load dampening values need to applied to make these calculation more meaningful.

Forward-Looking Frequency Response

Frequency Response Forward-Looking Analysis

- Under active development
  - Ongoing work with the interconnections on the development of frequency response models
  - Plans for model development to complete by Q4 2017
- Models and analysis to be completed in 2018
  - Analysis results included in Long-Term Reliability Assessment Reports starting in 2018
- In the future, the Planning Committee’s Reliability Assessment Subcommittee (RAS) will provide oversight for Forward-Looking Frequency Response Analysis

Questions and Answers