NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

2016 Frequency Response Annual Analysis

September 2016

RELIABILITY | ACCOUNTABILITY

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Preface

The North American Electric Reliability Corporation (NERC) is a not-for-profit international regulatory authority whose mission is to assure the reliability of the bulk power system (BPS) in North America. NERC develops and enforces Reliability Standards; annually assesses seasonal and long-term reliability; monitors the BPS through system awareness; and educates, trains, and certifies industry personnel. NERC's area of responsibility spans the continental United States, Canada, and the northern portion of Baja California, Mexico. NERC is the electric reliability organization (ERO) for North America, subject to oversight by the Federal Energy Regulatory Commission (FERC) and governmental authorities in Canada. NERC's jurisdiction includes users, owners, and operators of the BPS, which serves more than 334 million people.

The North American BPS is divided into eight Regional Entity (RE) boundaries as shown in the map and corresponding table below.
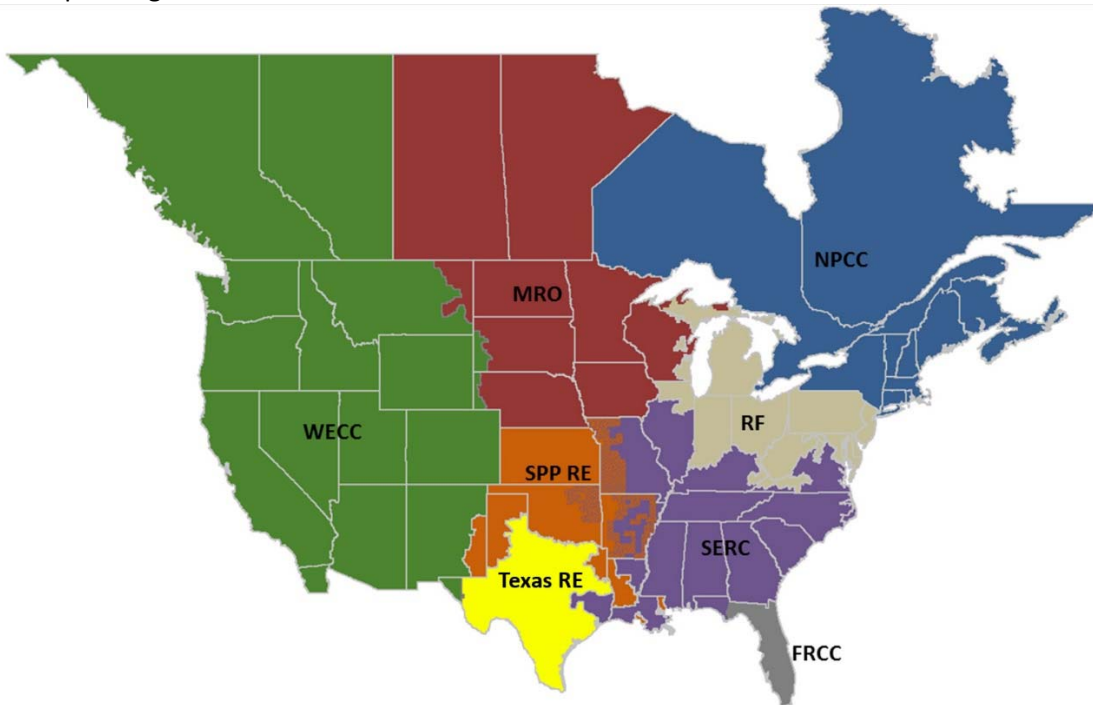
The North American BPS is divided into eight Regional Entity (RE) boundaries. The highlighted areas denote overlap as some load-serving entities participate in one Region while associated transmission owners/operators participate in another.

FRCC	Florida Reliability Coordinating Council
MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
SPP RE	Southwest Power Pool Regional Entity
Texas RE	Texas Reliability Entity
WECC	Western Electricity Coordinating Council

This Report

This report is the 2016 annual analysis of frequency response performance for the administration and support of NERC Reliability Standard BAL-003-1 – Frequency Response and Frequency Bias Setting. It provides an update to the statistical analyses and calculations contained in the *2012 Frequency Response Initiative Report* approved by the NERC Resources Subcommittee and Operating Committee and accepted by the NERC Board of Trustees. No changes are proposed to the procedures recommended in that report.

This report, prepared by NERC staff,[1] contains the analysis and annual recommendations for the calculation of the Interconnection Frequency Response Obligation (IFRO) for each of the four electrical interconnections of North America for the operational year 2017 (December 2016 through November 2017). This includes:

- Statistical analysis of the interconnection frequency characteristics for the period January 1, 2012, through December 31, 2015.[2]

- Calculation of adjustment factors from BAL-003-1 frequency response events.

- Dynamics analysis of the recommended IFROs.

- Analysis of frequency profiles for each interconnection.

This report was accepted by the Resources Subcommittee on August 25, 2016.

This report was accepted by the Operating Committee on September 30, 2016.

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[1] Prepared jointly by the System Analysis and Performance Analysis departments.
[2] From the *2016 State of Reliability* report, available at: http://www.nerc.com/pa/RAPA/PA/Pages/default.aspx.

Executive Summary

Recommendations

The following recommendations provide the IFRO values following the IFRO formulae outlined as per BAL-003-1, as well as actions that should be taken to address inconsistencies in the IFRO calculation identified in this year's analysis. While the IFRO values are recommended to be frozen for operating year 2017 (December 2016 through November 2017), the IFRO values are also provided for reference.

In accordance with the BAL-003-1 detailed implementation plan (and as a condition of approval by the Resources Subcommittee and the Operating Committee), these analyses are performed annually and the results published by November 15 each year, starting in 2015.

> **Interconnection Frequency Response Obligation (IFRO)**
> The IFRO values are recommended to be fixed at the values calculated in the 2015 FRAA and currently in effect, until inconsistencies in the IFRO calculation outlined in this section are addressed.
>
> The IFROs are considered to be the minimum frequency response necessary for the interconnections to maintain reliability and avoid tripping load by under frequency load shedding programs. It has no direct relationship to Frequency Bias setting used by Balancing Authorities to prevent withdrawal of primary frequency response by automatic generator control (AGC) action.

1. Due to inconsistencies outlined in the Findings section of this report, the IFRO values for operating year 2017 (December 2016 through November 2017) shall remain the same values as calculated in the 2015 FRAA report for operating year 2016, shown in Table A1.

Table A1: Recommended IFROs for Operating Year 2017					
	Eastern (EI)	**Western (WI)**	**Texas (TI)**	**Québec (QI)**	**Units**
IFRO	**-1,015**	**-858**	**-381**	**-179**	**MW/0.1Hz**

2. The NERC Resources Subcommittee should develop a Standard Authorization Request (SAR) to revise the IFRO calculation in BAL-003-1 due to inconsistencies identified in the 2016 Frequency Response Annual Analysis (FRAA) such as the IFRO values with respect to Point C and varying Value B, the Eastern Interconnection Resource Contingency Protection Criteria, event selection criteria, and evaluation of t_0.

3. The Resource Contingency Protection Criteria for each interconnection should be revised to help ensure sufficient primary frequency response is maintained. The Eastern Interconnection uses the "largest resource event in last 10 years", which is the 4 August 2007 event. The Standard Authorization Request (SAR) should revisit this issue for modifications to BAL-003-1 standard, and the Resources Subcommittee should recommend how the events are selected for each interconnection.

4. Many events, particularly in the Eastern Interconnection due to its large synchronous inertia, tend to have a frequency nadir point that exceeds the t_0[3]+12 seconds specified in BAL-003-1. Therefore, some events are characterized with a Point C value that is only partially down the arresting period of the event and does not accurately reflect the actual nadir. BAL-003-1 should be modified to allow for accurate representation of the Point C nadir value if exceeding t_0+12 seconds. The actual event nadir can occur at any time, including beyond the time period used for calculating Value B (t_0+20 through t_0+52 seconds), and may be the value known as Point C' which typically occurs from 72 to 95 seconds after t_0.

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[3] t_0 is defined as the time of the event.

1. The IFROs that were calculated for operating year 2017 (December 2016 through November 2017) are shown in Table A2. However, those values should NOT be used for operating year 2017, as noted in recommendation 1 and are provided here for reference (continuity of IFRO calculations for each year).

Table A2: Calculated IFROs for Operating Year 2017 using IFRO Formulae					
	Eastern (EI)	Western (WI)	Texas (TI)	Québec (QI)	Units
Starting Frequency	59.974	59.967	59.967	59.968	Hz
Max. Allowable Delta Frequency	0.435	0.298	0.410	0.947	Hz
Resource Contingency Protection Criteria	4,500	2,626	2,750	1,700	MW
Credit for Load Resources	N/A	120	1,193	N/A	MW
IFRO	**-1,034**	**-841**	**-380**	**-179**	**MW/0.1Hz**
Absolute Value of IFRO	**1,034**	**841**	**380**	**179**	**MW/0.1Hz**
Absolute Value of Current Interconnection Frequency Response Performance[4]	2,424	1,344	690	610	MW/0.1Hz
2016 IFRO as a % of Interconnection Load[5]	0.170	0.526	0.532	0.469	

2. Frequency response withdrawal continues to be a predominant characteristic in the Eastern Interconnection, with 37 out of 84 events with a secondary nadir (Point C') lower than the initial frequency nadir (Point C). The BC'$_{ADJ}$ adjustment factor introduced in the 2012 Frequency Response Initiative Report should continue to be tracked for the Eastern Interconnection.

3. Frequency response recovery phase (Value B) is improving in the Eastern Interconnection, with the CB$_R$ ratio increasing by 0.019; however, there is no attendant improvement in Point C. This is indicative of success in the initiative to improve Eastern Interconnection primary frequency response of the conventional generator fleet. The ratio itself is still drastically lower than the other interconnections (1.071 for the Eastern Interconnection). In the Western Interconnection, the CB$_R$ ratio decreased by 0.032; however, there are not significant trends in Value B or Point C and the ratio is still at 1.566. NERC should continue to track the characteristic shape of frequency response events for each interconnection in order to trend interconnection-wide performance of frequency in the recovery phase of the response.

4. The CB$_R$ ratio in the IFRO calculation couples Point C and Value B together, resulting in IFRO trends that do not align with the intent of the standard. Improvement in Value B with no change in Point C (improving recovery phase) would result in higher obligation to be carried, essentially penalizing improved performance. This should be addressed as part of the revision of the IFRO calculation in the BAL-003-1 Reliability Standard.

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[4] Based on Interconnection Frequency Response performance from Appendix E of the *2016 State of Reliability* report. By interconnection: EI = -2,424 MW / 0.1Hz, WI = -1,344 MW / 0.1Hz, TI = -690 MW / 0.1Hz, and QI = -610 MW/0.1 Hz.

[5] Draft Interconnection projected Total Internal Demands to be used in the *2016 NERC Long-Term Reliability Assessment* (2017 summer demand): EI = 609,946 MW, WI = 159,915 MW, TI = 71,416 MW, and QI (2016-2017 winter demand) = 38,150 MW. NOTE: These values are not finalized for the 2016 LTRA; draft numbers provided here for illustration purposes.

1. The NERC Resources Subcommittee (RS) should consider collecting data on individual unit performance for selected frequency response events to more comprehensively understand the frequency characteristics for each interconnection. This may include an assessment of the Eastern, Western, and Texas Interconnections. These efforts are intended to continue to improve primary frequency response.

2. In their dynamic case creation process, each interconnection should study the Resource Loss Protection Criteria contingency used by NERC for BAL-003-1 implementation to ensure that the simulation numerically converges[6]. NERC System Analysis worked with the case creation groups to mitigate errors in the dynamics cases prior to simulating the response; these numerical stability errors should not be present for the contingency under consideration. This may require the case creation entities in each interconnection to mitigate issues identified in some of the renewables models.

Findings

1. Analysis of the behavior of the IFRO calculations for each interconnection in response to trends in frequency response performance has identified inconsistencies in the IFRO calculation that need to be addressed immediately. Namely, the following findings are important to highlight:

   a. The ratio between Point C and Value B (CBR) is a multiplicative factor in the IFRO formulae, which couples these two quantities together in the formulation of the IFRO. Table A3 shows how the IFRO calculation will change based on relative movement of the differences between Value A and Point C and Value B (↑: increase, ↓: decrease, – : no change).

Table A3: IFRO Movement in Relation to Point C and Values A and B				
Scenario	**A-B**	**A-C**	**CB$_R$**	**IFRO**
1	–	–	–	–
2	–	↑	↑	↑
3	↑	–	↓	↓
4	–	↓	↓	↓
5	↓	–	↑	↑
6	↑	↑	–	–
7	↓	↓	–	–

   The original intent of the IFRO calculation was to ensure Scenario 2 was covered, where an increasing difference between Point A and the frequency nadir would result in an increased IFRO. However, the calculation also causes Scenarios 3 and 5 to have an adverse effect on the IFRO calculation. Scenario 3 is the situation where Value B is declining and results in a lower IFRO; conversely, Scenario 5 is the situation where Value B is improving (increasing) and results in a higher IFRO. The IFRO should not penalize an interconnection for better performance of frequency response measure against Value B nor reduce the obligation for poor performance.

   b. The statistically determined value for Starting frequency is important to account for a statistically determined value for which Point A can be assumed. However, the Delta Frequency should capture

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[6] Does not cause any numerical issues due to problematic models.

an acceptable value of Point B that is based on historic trends of frequency nadir compared with Value B. This will ensure a decoupling of these values in the IFRO calculation.

2. The IFRO values calculated in this year's analysis compare closely with the IFRO values calculated in the 2015 FRAA; however, because of the inconsistencies identified in this analysis it is most appropriate to 'freeze' the IFRO values to those values currently in effect (2016 operating year as determined in the 2015 FRAA).

3. The University of Tennessee-Knoxville (UTK) FNET[7] data used in the analysis has seen significant improvement in data quality, greatly simplifying and improving annual analysis of frequency performance and ongoing tracking of frequency response events. In addition, NERC uses data quality checks to flag additional bad one-second data including a bandwidth filter, least squares fit, and derivative checking. This slightly modified data checking techniques resulted in no or minimal (+/- 0.001 Hz) change to starting frequency.

4. As with the previous year's analysis, all frequency event analysis is using sub-second data from the FNET system frequency data recorders (FDRs). This eliminates the need for the CC_{ADJ} factor because the actual frequency nadir was able to be accurately captured.

5. The Frequency Response Analysis Tool[8] (FRAT) is being used by the NERC Bulk Power System Awareness (BPSA) group for frequency event tracking in support of the NERC Frequency Working Group (FWG). The tool has significantly expedited and streamlined interconnection frequency response analysis. The tool provides an effective means of compiling frequency response events and generating a database of necessary values for adjustment factor calculations.

6. ERCOT underwent mid-year changes during the 2015 operating year for their process in procuring frequency-responsive load resources which are used to calculate their credit for load resources (CLR). In the Texas Interconnection IFRO calculation, CLR is based on a statistical analysis of procured CLR. Therefore, the changes are reflected in the statistically determined CLR calculation. CLR increased by 12 MW to 1,193 MW for the 2016 FRAA.

7. The ratio between Point C and Value B (CB_R) decreased in the Western Interconnection by -0.032 and increased in the Eastern Interconnection by 0.019. Trends in Point C and Value B for the Western Interconnection do not identify any noticeable trends in performance. Trends in the Eastern Interconnection show improved performance in Value B recovery period with no significant change in Point C (signifying improved governor response as an interconnection).

8. Dynamics simulations of the Eastern, Western, and Texas Interconnections for the recommended IFROs showed levels of primary frequency response to be adequate to avoid tripping of the first stage of the interconnection underfrequency load shedding (UFLS) systems. Light-load cases were used for all three of these analyses.

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[7] Operated by the Power Information Technology Laboratory at the University of Tennessee, FNET is a low-cost, quickly deployable GPS-synchronized wide-area frequency measurement network. High-dynamic accuracy FDRs are used to measure the frequency, phase angle, and voltage of the power system at ordinary 120 V outlets. The measurement data are continuously transmitted via the Internet to the FNET servers hosted at the University of Tennessee and Virginia Tech.

[8] Developed by Pacific Northwest National Laboratory (PNNL).

Interconnection Frequency Characteristic Analysis

Frequency Variation Statistical Analysis

NERC staff performs a statistical analysis[9] annually of the variability of frequency for each of the four interconnections using a window of one-second-measured frequency. For this report's analysis, frequency data from 2012–2015 was used and is summarized in Table 1.

This variability accounts for items such as time-error correction (TEC), variability of load, interchange, and frequency over the course of a normal day. It also accounts for all frequency excursion events.

One-Second Frequency Data
One-second frequency data for the frequency variation analysis is provided by UTK. The data is sourced from FDRs in each interconnection. The median value among the higher resolution FDRs is down-sampled to one sample per second and filters are applied to ensure data quality.

Table 1: Interconnection Frequency Variation Analysis				
Value	**Eastern**	**Western**	**Texas**	**Québec**
Time Frame (Operating Years)	2012-2015	2012-2015	2012-2015	2012-2015
Number of Samples	124,060,984	124,706,445	121,426,164	121,782,971
Filtered Samples (% of total)	98.3%	98.8%	96.2%	96.5%
Expected Value (Hz)	60.000	59.999	59.999	59.999
Variance of Frequency (σ^2)	0.00023	0.00036	0.00037	0.00037
Standard Deviation (σ)	0.01505	0.01895	0.01915	0.01936
50% percentile (median)	59.999	59.998	60.000	59.998
Starting Frequency (F_{start}) (Hz)	**59.974**	**59.967**	**59.967**	**59.968**

The starting frequencies encompass all variations in frequency including changes to the target frequency during TEC. This eliminates the need to expressly evaluate TEC as a variable in the IFRO calculation. The starting frequency for the calculation of IFROs is the 5th percentile lower tail of samples from the statistical analysis, which represents a 95 percent chance that frequencies will be at or above that value at the start of any frequency event.

Figures 1-4 show the probability density function of frequency for each interconnection. The vertical red line represents the 5th percentile frequency for each interconnection, representing the value at which interconnection frequency will statistically be greater than 95% of the time. A more detailed description of the probability density functions is provided in Appendix A.

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[9] Refer to the 2012 *Frequency Response Initiative* report for details on the statistical analyses used.
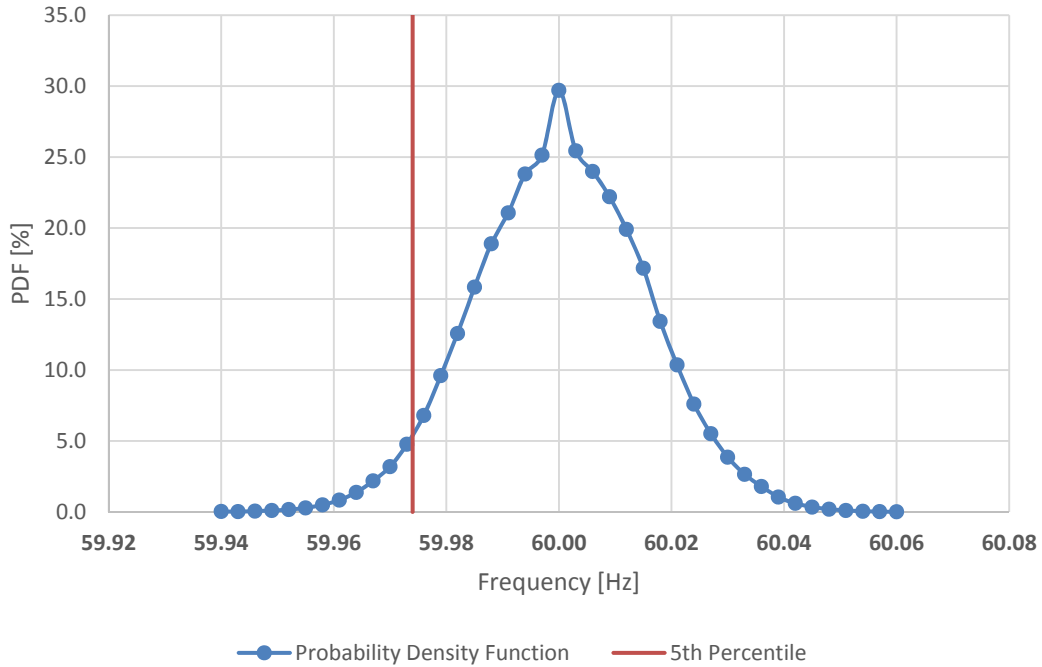
Figure 1: Eastern Interconnection 2012–2015 Probability Density Function of Frequency
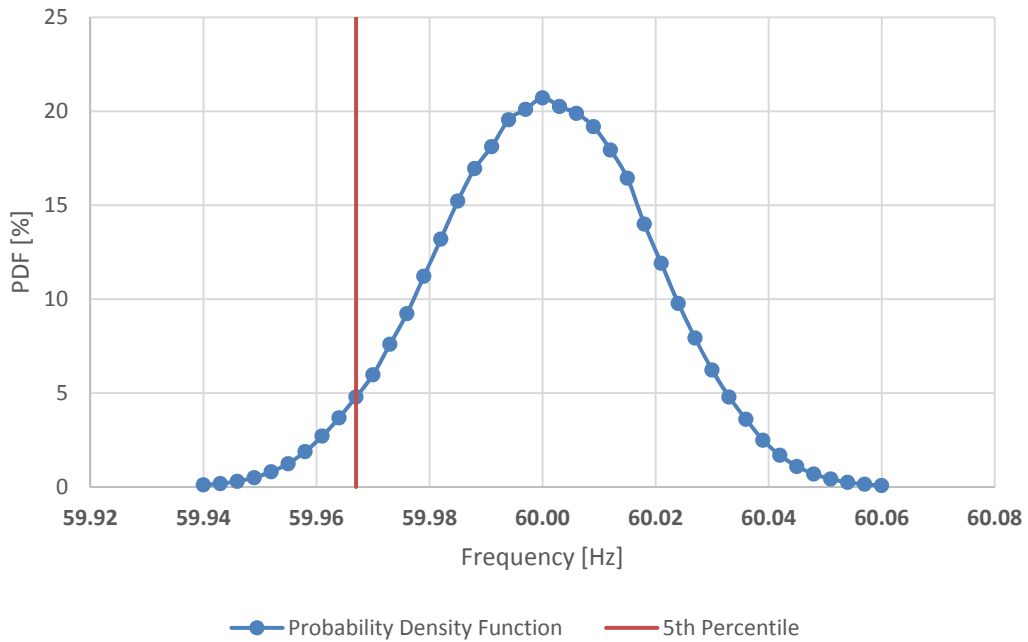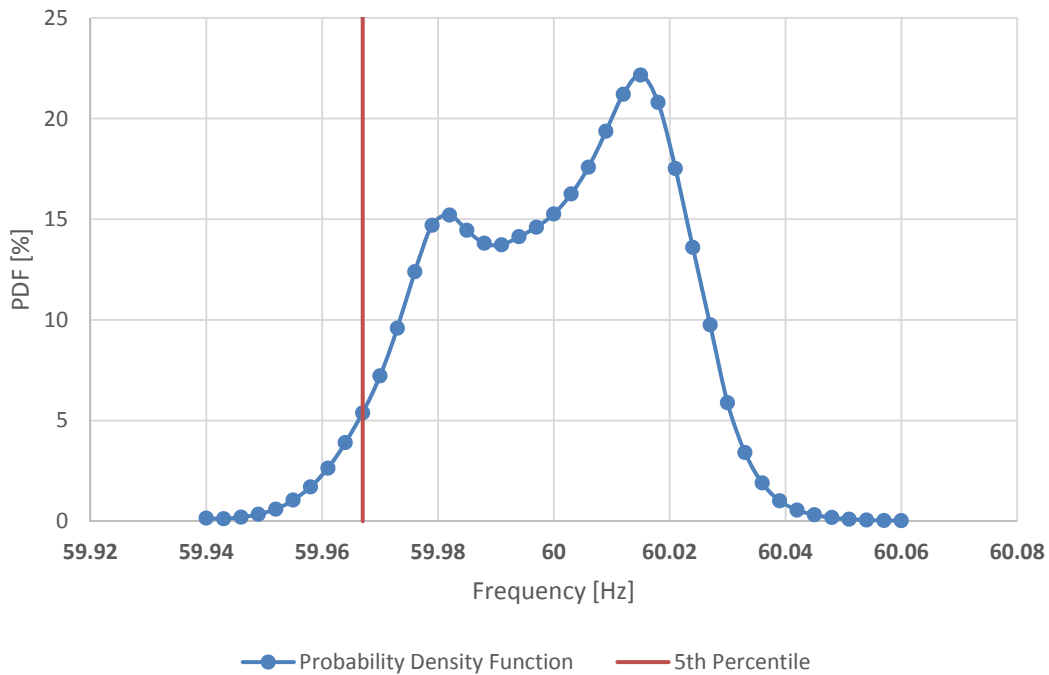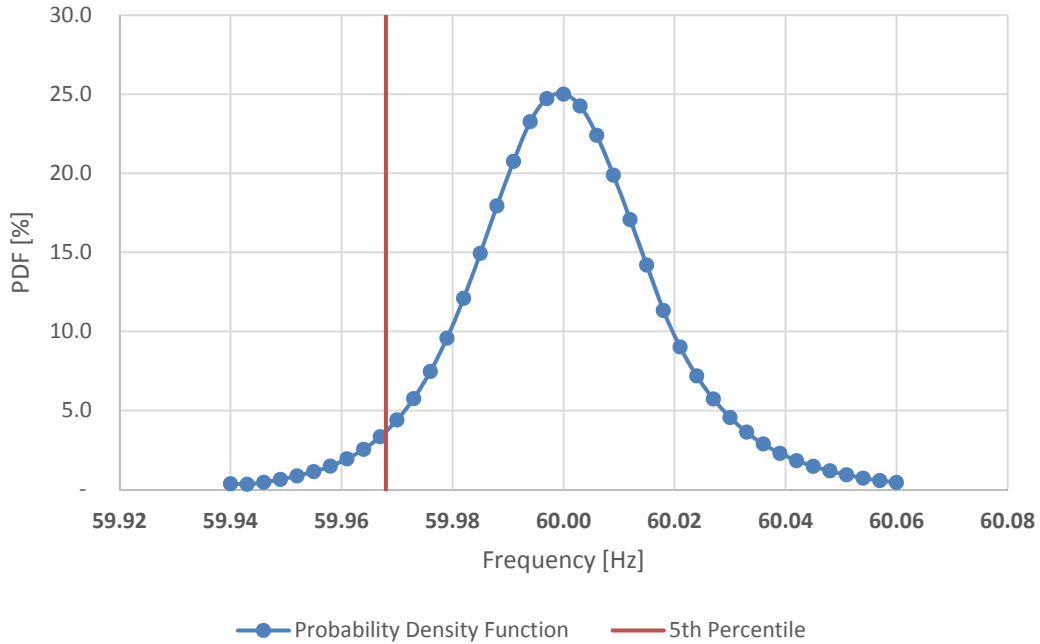

Figure 2: Western Interconnection 2012–2015 Probability Density Function of Frequency

Figure 3: Texas Interconnection 2012–2014 Probability Density Function of Frequency

The probability density function of frequency for Texas has shown a dramatic change in 2015 when Standard TRE BAL-001 went into full effect in April of 2015. That standard requires all resources to provide primary frequency response with a ±16.7 mHz deadband with non-step, proportional response implementation. As a result, anytime frequency exceed 60.017 Hz, resources automatically curtail themselves. That has resulted in far less operation in frequencies above the deadband, since all resources, including wind, are backing down. This is exhibited in Figure 3 as a concentration of the probability density around the 60.017 Hz deadband and a reduction in the probability occurrences beyond that point. Similar behavior is not exhibited at the low deadband of 59.983 Hz because most wind resources are operated at maximum output and cannot increase when frequency falls below the deadband. Additional analysis of this change is contained in Appendix A.

Figure 4: Québec Interconnection 2012–2014 Probability Density Function of Frequency

Changes in Starting Frequency

A comparison of expected frequencies and starting frequencies between the 2016 and 2015 frequency variability analyses is shown in Table 2. Expected frequencies are unchanged for all interconnections. Starting frequencies are unchanged for the Eastern and Western Interconnections; Texas and Québec Interconnections had a variation in starting frequencies of less than 0.001 Hz.

Table 2: Comparison of Interconnection Frequency Statistics (Hz)			
Expected Frequencies			
	2015 Analysis	2016 Analysis	Change
Eastern	60.000	60.000	0.000
Western	59.999	59.999	0.000
Texas	59.999	59.999	0.000
Québec	59.999	59.999	0.000
Starting Frequencies			
Eastern	59.974	59.974	0.000
Western	59.967	59.967	0.000
Texas	59.966	59.967	0.001
Québec	59.969	59.968	-0.001

Determination of Interconnection Frequency Response Obligations

Tenets of IFRO

The IFRO is the minimum amount of frequency response that must be maintained by an interconnection. Each Balancing Authority in the interconnection should be allocated a portion of the IFRO that represents its minimum responsibility. To be sustainable, Balancing Authorities that may be susceptible to islanding may need to carry additional frequency-responsive reserves to coordinate with their UFLS plans for islanded operation.

A number of methods to assign the frequency response targets for each interconnection can be considered. Initially, the following tenets should be applied:

1. A frequency event should not trip the first stage of regionally approved UFLS systems within the interconnection.

2. Local tripping of first-stage UFLS systems for severe frequency excursions, particularly those associated with protracted faults or on systems on the edge of an interconnection, may be unavoidable.

3. Other frequency-sensitive loads or electronically coupled resources may trip during such frequency events, as is the case for photovoltaic (PV) inverters.

4. It may be necessary in the future to consider other susceptible frequency sensitivities (e.g., electronically coupled load common-mode sensitivities).

UFLS is intended to be a safety net to prevent system collapse from severe contingencies. Conceptually, that safety net should not be violated for frequency events that happen on a relatively regular basis. As such, the resource loss protection criteria were selected through the Frequency Response Initiative 2012 analysis to avoid violating regionally approved UFLS settings.

IFRO Formulae

The following are the formulae that comprise the calculation of the IFROs:

$$DF_{Base} = F_{Start} - UFLS$$

$$DF_{CBR} = \frac{DF_{Base}}{CB_R}$$

$$MDF = DF_{CBR} - BC'_{Adj}$$

$$ARLPC = RLPC - CLR$$

$$IFRO = \frac{ARLPC}{MDF}$$

Where:

- DF_{Base} is the base delta frequency.

- F_{Start} is the starting frequency determined by the statistical analysis.

- UFLS is the highest UFLS trip set point for the interconnection.

- CB_R is the statistically determined ratio of the Point C to Value B.

- DF$_{CBR}$ is the delta frequency adjusted for the ratio of Point C to Value B.

- BC'$_{ADJ}$ is the statistically determined adjustment for the event nadir occurring below the Value B (Eastern Interconnection only) during primary frequency response withdrawal.

- MDF is the maximum allowable delta frequency.

- RLPC is the resource loss protection criteria.

- CLR is the credit for load resources.

- ARLPC is the adjusted resource loss protection criteria adjusted for the credit for load resources.

- IFRO is the interconnection frequency response obligation.

Note: The CC$_{ADJ}$ adjustment has been eliminated because of the use of sub-second data for this year's analysis of the interconnection frequency events. The CC$_{ADJ}$ adjustment had been used to correct for the differences between one-second and sub-second Point C observations for frequency events. This also eliminates the DF$_{CC}$ term from the formulae.

Determination of Adjustment Factors
Adjustment for Differences between Value B and Point C (CB$_R$)

All of the calculations of the IFRO are based on avoiding instantaneous or time-delayed tripping of the highest set point (step) of UFLS, either for the initial nadir (Point C), or for any lower frequency that might occur during the frequency event. However, as a practical matter, the ability to measure the tie line and loads for a Balancing Authority is limited to SCADA scan rates of one to six seconds. Therefore, the ability to measure frequency response at the Balancing Authority level is limited by the SCADA scan rates available to calculate Value B. To account for the issue of measuring frequency response as compared with the risk of UFLS tripping, an adjustment factor (CB$_R$) is calculated from the significant frequency disturbances between December 1, 2011 to November 30, 2015, which captures the relationship between Value B and Point C. This resulted in the number of events shown in Table 3.

> **Sub-Second Frequency Data Source**
> Frequency data used for calculating all of the adjustment factors used in the IFRO calculation comes from the UTK FNet system. Six minutes of data is used for each frequency disturbance analyzed, 1 minute prior to the event and 5 minutes following the start of the event. All event data is provided at a higher resolution (10 samples-per-second) as a median frequency from all the available FDRs for that event.

Analysis Method

The IFRO is the minimum performance level that the Balancing Authorities in an interconnection must meet through their collective frequency response to a change in frequency. This response is also related to the function of the Frequency Bias setting in the area control error (ACE) equation of the Balancing Authorities for the longer term. The ACE equation looks at the difference between scheduled frequency and actual frequency, times the Frequency Bias setting to estimate the amount of megawatts that are being provided by load and generation within the Balancing Authority. If the actual frequency is equal to the scheduled frequency, the Frequency Bias component of ACE must be zero.

When evaluating some physical systems, the nature of the system and the data resulting from measurements derived from that system do not fit the standard linear regression methods that allow for both a slope and an intercept for the regression line. In those cases, it is better to use a linear regression technique that represents the system correctly. Since the IFRO is ultimately a projection of how the interconnection is expected to respond to changes in frequency related to a change in megawatts (resource loss or load loss), there should be no

expectation of frequency response without an attendant change in megawatts. It is this relationship that indicates the appropriateness of using regression with a forced fit through zero.

Determination of C-to-B Ratio (CB$_R$)

The evaluation of data to determine the C-to-B ratio (CB$_R$) to account for the differences between arrested frequency response (to the nadir, Point C) and settled frequency response (Value B) is also based on a physical representation of the electrical system. Evaluation of this system requires investigation of the meaning of an intercept. The CB$_R$ is defined as the difference between the pre-disturbance frequency and the frequency at the maximum deviation in post-disturbance frequency, divided by the difference between the pre-disturbance frequency and the settled post-disturbance frequency.

$$CB_R = \frac{Value\ A - Point\ C}{Value\ A - Value\ B}$$

A stable physical system requires the ratio to be positive; a negative ratio indicates frequency instability or recovery of frequency greater than the initial deviation. The CB$_R$ adjusted for confidence (Table 3) should be used to compensate for the differences between Point C and Value B.

Table 3: Analysis of Value B and Point C (CB$_R$)					
Interconnection	Number of Events Analyzed	Mean	Standard Deviation	95% Confidence	CB$_R$ Adjusted for Confidence
Eastern	84	1.037	0.185	0.034	1.071
Western	60	1.525	0.192	0.041	1.566
Texas	155	1.576	0.372	0.050	1.626
Québec	102	3.964	1.000	0.164	1.550

The Eastern Interconnection exhibits a frequency response characteristic that often has Value B below Point C, and the CB$_R$ value for the Eastern Interconnection has historically been below 1.000, therefore the CB$_R$ has been limited to 1.000. However, the calculated CB$_R$ in this year's analysis indicates a value above 1.000, and no limitation is required.

The Québec Interconnection's resources are predominantly hydraulic and are operated to optimize efficiency, typically at about 85 percent of rated output. Consequently, most generators have about 15 percent headroom to supply primary frequency response. This results in a robust response to most frequency events, exhibited by high rebound rates between Point C and the calculated Value B. For the 81 frequency events in their event sample, Québec's CB$_R$ value would be 4.13, or two to four times the CB$_R$ values of other interconnections. Using the same calculation method for CB$_R$ would effectively penalize Québec for their rapid rebound performance and make their IFRO artificially high. Therefore, the method for calculating the Québec CB$_R$ was modified.

Québec has an operating mandate for frequency responsive reserves to prevent tripping their 58.5 Hz (300 millisecond trip time) first-step UFLS for their largest hazard at all times, effectively protecting against tripping for Point C frequency excursions. Québec also protects against tripping a UFLS step set at 59.0 Hz that has a 20-second time delay, which protects them from any sustained low-frequency Value B and primary-frequency response withdrawals. This results in a Point C to Value B ratio of 1.5. To account for the confidence interval, 0.05 is then added, making the Québec CB$_R$ equal 1.550.

Point C Analysis – One-Second versus Sub-second Data (CC$_{ADJ}$) Eliminated

Calculation of all of the IFRO adjustment factors for the 2016 FRAA solely utilized sub-second measurements from FNET FDRs. Data at this resolution accurately reflect the Point C nadir; therefore, a CC$_{ADJ}$ factor is no longer required and has been eliminated.

Adjustment for Primary Frequency Response Withdrawal (BC'$_{ADJ}$)

At times, the nadir for a frequency event occurs after Point C, defined in BAL-003-1 as occurring in the T+0 to T+12 second period, during the Value B averaging period (T+20 through T+52 seconds), or later. For purposes of this report, the later-occurring nadir is termed Point C'. This lower nadir is symptomatic of primary frequency response withdrawal, or squelching, by unit-level or plant-level outer-loop control systems. Withdrawal is most prevalent in the Eastern Interconnection.

Primary frequency response withdrawal is important depending on the type and characteristics of the generators in the resource dispatch, especially during light-load periods. Therefore, an additional adjustment to the maximum allowable delta frequency for calculating the IFROs was statistically developed. This adjustment is used whenever withdrawal is a prevalent feature of frequency events.

Table 4 shows a summary of the events for each interconnection where the C' value was lower than Value B (averaged from T+20 through T+52 seconds) and Point C for the period of January 2012 through December 2015. The statistical analysis is performed on the events with C' value lower than Value B to determine the adjustment factor BC'$_{ADJ}$.

Table 4: Statistical Analysis of the Adjustment for C' Nadir (BC'$_{adj}$)						
Interconnection	Number of Events Analyzed	C' Lower than B	C' Lower than C	Mean Difference	Standard Deviation	BC'ADJ (95% Quantile)
Eastern	84	54	37	0.006	0.004	0.007
Western	60	29	0	N/A	N/A	N/A
Texas	155	44	3	N/A	N/A	N/A
Québec	102	35	0	N/A	N/A	N/A

Although events with C' lower than C have been identified in the Texas Interconnection, there is only statistically significant data to apply this adjustment factor to the Eastern Interconnection. This will continue to be monitored moving forward to track these trends in C' performance. Therefore, a BC'$_{ADJ}$ is only needed for the Eastern Interconnection; no BC'$_{ADJ}$ is needed for the other three interconnections. The 95 percent quantile value is used for the Eastern Interconnection BC'$_{ADJ}$ of 7 mHz (see Table 4) to account for the statistically expected Point C' value of a frequency event.

In the Eastern Interconnection, the Point C' nadir occurs 72-92 seconds after the start of the event[10] 90% of the time, which is well beyond the time frame for calculating Value B.

Low-Frequency Limit

The low-frequency limit to be used for the IFRO calculations should be the highest step in the interconnection for regionally approved UFLS systems.

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[10] The timing of the C' occurrence is consistent with outer-loop plant and unit controls causing withdrawal of unit frequency response.

Table 5: Low-Frequency Limits (Hz)	
Interconnection	**Highest UFLS Trip Frequency**
Eastern	59.5
Western	59.5
Texas	59.3
Québec	58.5

The highest UFLS set point in the Eastern Interconnection is 59.7 Hz in FRCC, while the highest set point in the rest of the interconnection is 59.5 Hz. The FRCC 59.7 Hz first UFLS step is based on internal stability concerns, and is meant to prevent the separation of the Florida peninsula from the rest of the interconnection. FRCC concluded that the IFRO starting point of 59.5 Hz for the Eastern Interconnection is acceptable in that it imposes no greater risk of UFLS operation for an interconnection resource loss event than for an internal FRCC event.

Protection against tripping the highest step of UFLS does not ensure generation that has frequency-sensitive boiler or turbine control systems will not trip. Severe system conditions might drive the frequency and voltage to levels that present a combination of conditions to control systems that may cause some generation to trip. Severe rates-of-change occurring in voltage or frequency might actuate volts-per-hertz relays which would also trip some units. Similarly, some combustion turbines may not be able to sustain operation at frequencies below 59.5 Hz.

Electronically coupled resources may be susceptible to extremes in frequency. Laboratory testing by Southern California Edison of inverters used on residential and commercial scale PV systems revealed a propensity to trip at about 59.4 Hz, which is 200 mHz above the expected 59.2 Hz prescribed in IEEE Standard 1547 for distribution-connected PV systems rated at or below 30 kW (57.0 Hz for larger installations). This could become problematic in the future in areas with a high penetration of PV resources; however, IEEE Standard 1547 is being revised and will include significantly wider voltage ride-through capability.

Credit for Load Resources

The Texas Interconnection depends on contractually interruptible (an Ancillary Service) demand response that automatically trips at 59.7 Hz by underfrequency relay to help arrest frequency declines. A credit for load resources[11] (CLR) is made for the resource contingency for the Texas Interconnection.

The amount of CLR available any given time varies by different factors including its usage in the immediate past. NERC performed statistical analysis on hourly available CLR over a two year period from January 2014 through December 2015, similar to the approach used in the 2015 FRAA. Statistical analysis indicated that 1,193 MW of CLR is available 95 percent of the time. Therefore, a CLR adjustment of 1,193 MW is applied in the calculation of the Texas Interconnection IFRO as a reduction to the loss of resources.

The 2015 CLR for Texas Interconnection is only 12 MW higher than the 1,181 MW adjustment in the 2015 IFRO calculation, showing consistency in the procurement and availability load resources to arrest frequency response in ERCOT.

> **ERCOT Credit for Load Resources (CLR)**
> Prior to April 2012, ERCOT was procuring 2,300 MW of Responsive Reserve Service (RRS) of which up to 50 percent could be provided by the load resources with under-frequency relays set at 59.70 Hz. Beginning April 2012 due to a change in market rules, the RRS requirement was increased from 2,300 MW to 2,800 MW for each hour, meaning load resources could potentially provide up to 1,400 MW of RRS.

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[11] Formerly called Load acting as a Resource, or LaaR.

Determination of Maximum Allowable Delta Frequencies

Because of the measurement limitation of the BA-level frequency response performance using Value B, IFROs must be calculated in "Value B space." Protection from tripping UFLS for the interconnections based on Point C, Value B, or any nadir occurring after point C, within Value B, or after T+52 seconds must be reflected in the maximum allowable delta frequency for IFRO calculations expressed in terms comparable to Value B.

Table 6 shows the calculation of the maximum allowable delta frequencies for each of the interconnections. All adjustments to the maximum allowable change in frequency are made to include:

- Adjustments for the differences between Point C and Value B.

- Adjustments for the event nadir being below Value C' (Eastern Interconnection only) due to primary frequency response withdrawal.

Table 6: Determination of Maximum Allowable Delta Frequencies					
	Eastern	**Western**	**Texas**	**Québec**	**Units**
Starting Frequency	59.974	59.967	59.967	59.968	Hz
Minimum Frequency Limit	59.500	59.500	59.300	58.500	Hz
Base Delta Frequency	0.474	0.467	0.667	1.468	Hz
CB_R[12]	1.071	1.566	1.626	1.550	Ratio
Delta Frequency (DF_{CBR})[13]	0.443	0.298	0.410	0.947	Hz
BC'_{ADJ}[14]	0.007	N/A	N/A	N/A	Hz
Max. Allowable Delta Frequency	0.435	0.298	0.410	0.947	Hz

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[12] Adjustment for the differences between Point C and Value B.

[13] DF_{CC}/CB_R

[14] Adjustment for the event nadir being below the Value B (Eastern Interconnection only) due to primary frequency response withdrawal.

Comparison of Maximum Allowable Delta Frequencies

The following is a comparison of the 2016 maximum allowable delta frequencies with the values from the 2015 *Frequency Response Annual Analysis* report.

Table 7a: Maximum Allowable Delta Frequency Comparison				
Eastern	**2015**	**2016**	**Change**	**Units**
Starting Frequency	59.974	59.974	0.000	Hz
Min. Frequency Limit	59.500	59.500	0.000	Hz
Base Delta Frequency	0.474	0.474	0.000	Hz
CC$_{ADJ}$	N/A	N/A	N/A	Hz
Delta Frequency (DF$_{CC}$)	0.474	0.474	0.000	Hz
CB$_R$	1.052	1.071	0.019	Ratio
Delta Freq. (DF$_{CBR}$)	0.450	0.443	-0.007	Hz
BC'$_{ADJ}$	0.007	0.007	0.000	Hz
Max. Allowable Delta Frequency	0.443	0.435	-0.007	Hz
Western	**2015**	**2016**	**Change**	**Units**
Starting Frequency	59.967	59.967	0.000	Hz
Min. Frequency Limit	59.500	59.500	0.000	Hz
Base Delta Frequency	0.467	0.467	0.000	Hz
CC$_{ADJ}$	N/A	N/A	N/A	Hz
Delta Frequency (DF$_{CC}$)	0.467	0.467	0.000	Hz
CB$_R$	1.598	1.566	-0.032	Ratio
Delta Freq. (DF$_{CBR}$)	0.292	0.298	0.006	Hz
BC'$_{ADJ}$	N/A	N/A	N/A	Hz
Max. Allowable Delta Frequency	0.292	0.298	0.006	Hz

In the Eastern Interconnection, the maximum allowable delta frequency value only changed by 7 mHz. The following are observations regarding maximum allowable delta frequency:

- CB$_R$ increased from 1.052 to 1.071, and therefore the delta frequency (DF$_{CBR}$) decreased by 7 mHz. The increase in CB$_R$ demonstrates a continued strength on Point C frequency nadir relative to Value B.

- BC'$_{ADJ}$ remained the same between 2015 and 2016, illustrating some degree of continued governor response withdrawal.

In the Western Interconnection, the maximum allowable delta frequency value changed by 6 mHz. The following are observations regarding maximum allowable delta frequency:

- Delta frequency (DF$_{CBR}$) increased by 6 mHz due to the CB$_R$ ratio decreasing by a factor of -0.032, illustrating a weaker Point C frequency nadir relative to Value B.

Table 7b: Maximum Allowable Delta Frequency Comparison				
Texas	**2015**	**2016**	**Change**	**Units**
Starting Frequency	59.966	59.967	0.001	Hz
Min. Frequency Limit	59.300	59.300	0.000	Hz
Base Delta Frequency	0.666	0.667	0.001	Hz
CC_{ADJ}	N/A	N/A	N/A	Hz
Delta Frequency (DF_{CC})	0.666	0.667	0.001	Hz
CB_R	1.619	1.626	0.007	Ratio
Delta Freq. (DF_{CBR})	0.411	0.410	-0.001	Hz
BC'_{ADJ}	N/A	N/A	N/A	Hz
Max. Allowable Delta Frequency	0.411	0.410	-0.001	Hz
Québec	**2015**	**2016**	**Change**	**Units**
Starting Frequency	59.969	59.968	-0.001	Hz
Min. Frequency Limit	58.500	58.500	0.000	Hz
Base Delta Frequency	1.469	1.468	-0.001	Hz
CC_{ADJ}	N/A	N/A	N/A	Hz
Delta Frequency (DF_{CC})	1.469	1.468	-0.001	Hz
CB_R	1.550	1.550	0.000	Ratio
Delta Freq. (DF_{CBR})	0.948	0.947	-0.001	Hz
BC'_{ADJ}	N/A	N/A	N/A	Hz
Max. Allowable Delta Frequency	0.948	0.947	-0.001	Hz

In the Texas Interconnection, the maximum allowable delta frequency value changed by 1 mHz. The following are observations regarding maximum allowable delta frequency:

- The CB_R factor increased by 0.007, and therefore the delta frequency (DF_{CBR}) only decreased by 1 mHz.

In the Québec Interconnection, the maximum allowable delta frequency value changed by 1 mHz.

Calculated IFROs

Table 8 shows the determination of IFROs for operating year 2017 (December 2016 through November 2017) under standard BAL-003-1 based on a resource loss equivalent to the recommended criteria in each interconnection. The maximum allowable delta frequency values have already been modified to include the adjustments for the differences between Value B and Point C (CB_R), the differences in measurement of Point C using one-second and sub-second data (CC_{ADJ}), and the event nadir being below the Value B (BC'_{ADJ}).

Table 8: Recommended IFROs					
	Eastern (EI)	Western (WI)	Texas (TI)	Québec (QI)	Units
Starting Frequency	59.974	59.967	59.967	59.968	Hz
Max. Allowable Delta Frequency	0.435	0.298	0.410	0.947	Hz
Resource Contingency Protection Criteria	4,500	2,626	2,750	1,700	MW
Credit for Load Resources	N/A	120[15]	1,193	N/A	MW
IFRO	**-1,034**	**-841**	**-380**	**-179**	**MW/0.1Hz**
Absolute Value of IFRO[16]	**1,034**	**841**	**380**	**179**	**MW/0.1Hz**
Absolute Value of Current Interconnection Frequency Response Performance[17]	2,424	1,344	690	610	MW/0.1Hz
2016 IFRO as a % of Interconnection Load[18]	0.170	0.526	0.532	0.469	

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[15] Based on the most updated information regarding load shedding for loss of 2 Palo Verde units, Western Interconnection CLR = 120 MW.

[16] The values of IFRO calculated here for the 2016 FRAA are shown for reference. It is recommended that the IFROs for operating year 2017 remain the same as the values calculated in the 2015 FRAA report due to inconsistencies identified in the IFRO formulae, as described in the Recommendations and Findings sections of the report.

[17] Based on Interconnection Frequency Response performance from Appendix E of the *2016 State of Reliability* report. By interconnection: EI = -2,424 MW / 0.1Hz, WI = -1,344 MW / 0.1Hz, TI = -690 MW / 0.1Hz, and QI = -610 MW/0.1 Hz.

[18] Draft Interconnection projected Total Internal Demands to be used in the *2016 NERC Long-Term Reliability Assessment* (2017 summer demand): EI = 609,946 MW, WI = 159,915 MW, TI = 71,416 MW, and QI (2016-2017 winter demand) = 38,150 MW. NOTE: These values are not finalized for the 2016 LTRA; draft numbers provided here for illustration purposes.

Comparison to Previous IFRO Values

The IFROs were first calculated and presented in the 2012 *Frequency Response Initiative Report*. Recommendations from that report called for an annual analysis and recalculation of the IFROs. The following is a comparison of the current IFROs and their key component values to those presented in the 2014 *Frequency Response Annual Analysis* report.

Table 9a: Interconnection IFRO Comparison				
Eastern	**2015**	**2016**	**Change**	**Units**
Starting Frequency	59.974	59.974	0.000	Hz
Max. Allowable Delta Frequency	0.443	0.435	-0.007	Hz
Resource Contingency Protection Criteria	4,500	4,500	0	MW
Credit for LR	N/A	N/A	N/A	MW
Absolute Value of IFRO	1,015	1,034	19	MW/0.1Hz
Western	**2015**	**2016**	**Change**	**Units**
Starting Frequency	59.967	59.967	0.000	Hz
Max. Allowable Delta Frequency	0.292	0.298	0.006	Hz
Resource Contingency Protection Criteria	2,626	2,626	0	MW
Credit for LR	120	120	0	MW
Absolute Value of IFRO	858	841	-17	MW/0.1Hz

The IFRO for the Eastern Interconnection increased by 19 MW/0.1 Hz, reflecting a slight change to frequency response characteristic. This is predominantly due to an increase in the ratio between Point C frequency nadir and Value B settling frequency.

The IFRO for the Western Interconnection decreased by 17 MW/0.1 Hz. Frequency response characteristic experienced a decrease in the ratio between Point C frequency nadir and Value B settling frequency, which will increase the maximum allowable delta frequency and hence the IFRO.

Table 9b: Interconnection IFRO Comparison				
Texas	**2015**	**2016**	**Change**	**Units**
Starting Frequency	59.966	59.967	0.001	Hz
Max. Allowable Delta Frequency	0.411	0.410	-0.001	Hz
Resource Contingency Protection Criteria	2,750	2,750	0	MW
Credit for LR	1,181	1,193	12	MW
Absolute Value of IFRO	381	380	-1	MW/0.1Hz
Québec	**2015**	**2016**	**Change**	**Units**
Starting Frequency	59.969	59.968	-0.001	Hz
Max. Allowable Delta Frequency	0.948	0.947	-0.001	Hz
Resource Contingency Protection Criteria	1,700	1,700	0	MW
Credit for LR	N/A	N/A	N/A	MW
Absolute Value of IFRO	179	179	0	MW/0.1Hz

The IFRO for the Texas Interconnection decreased by only 1 MW/0.1 Hz, representing a relatively stable frequency response characteristic over the time period of events analyzed.

The Québec Interconnection IFRO did not change, also representing a relatively stable frequency response characteristic over the time period of events analyzed.

Dynamics Analysis of Recommended IFROs

Off-peak dynamics analysis was performed of the recommended IFROs for the Eastern, Western, and Texas Interconnections to determine if those levels of primary frequency response are adequate to avoid tripping of the first stage of regionally approved UFLS systems in the interconnection. Light load cases prepared by each of the interconnections were used as the starting root case for the analyses. In each case, the dynamic governor or load responses were tuned until the primary frequency response of the interconnection closely matched the recommended IFRO value for the prescribed resource loss. In all three simulations, the effects of automatic generation control (AGC), which typically starts to influence frequency response in the 30-45 second timeframe, were not modeled.

In all three interconnections analyzed, frequency remained above the highest UFLS set point even with Interconnection frequency response degraded to the IFRO value.

Eastern Interconnection

For the Eastern Interconnection, the 2016 light load case developed by MMWG[19] for frequency response analysis was used as the starting root case. This case is supposed to more accurately represent actual governor settings, particularly related to governor response and squelched response. Figure 5 shows two figures. The figure on the left is the simulation of the resource loss protection criteria contingency with the case as-is. As the plot shows, the case did not converge for this relatively large contingency. The figure on the right shows the simulation results after working with the case to get it to converge for the duration of the simulation.
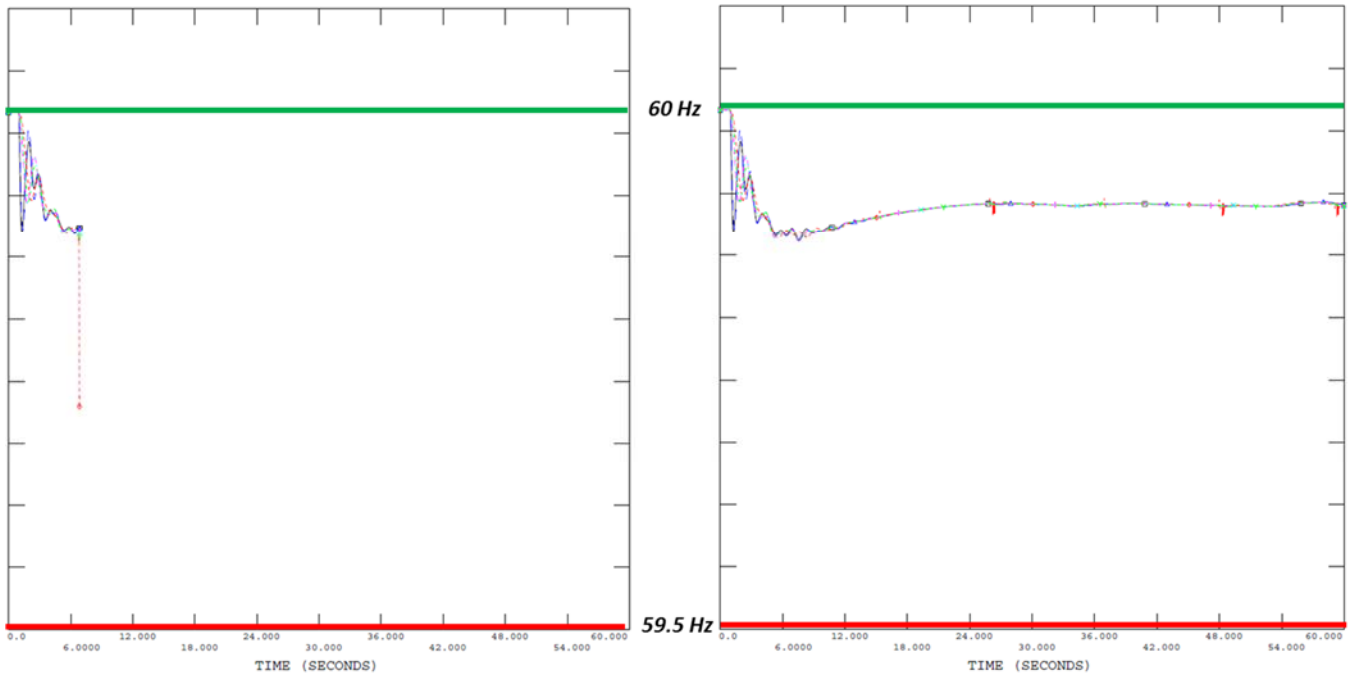

Figure 5: MMWG "Frequency Response Case" Simulations

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[19] Multiregional Modeling Working Group

The "frequency response case" simulation for the studied contingency did not accurately reflect frequency response characteristic in the Eastern Interconnection. The frequency responsiveness of the case was significantly degraded by disabling governors across the interconnection (Figure 6). The plot on the left shows the response after disabling governors; this resulted in slightly higher CB$_R$ than actual EI frequency response. Additional online units were squelched to get a lower response more representative of actual EI frequency response and the results of this simulation are shown on the right. This simulation, in conjunction with the vast degradation of FR towards the IFRO shows that the Eastern Interconnection is not likely to reach wide-area first stage UFLS for the studied contingency.
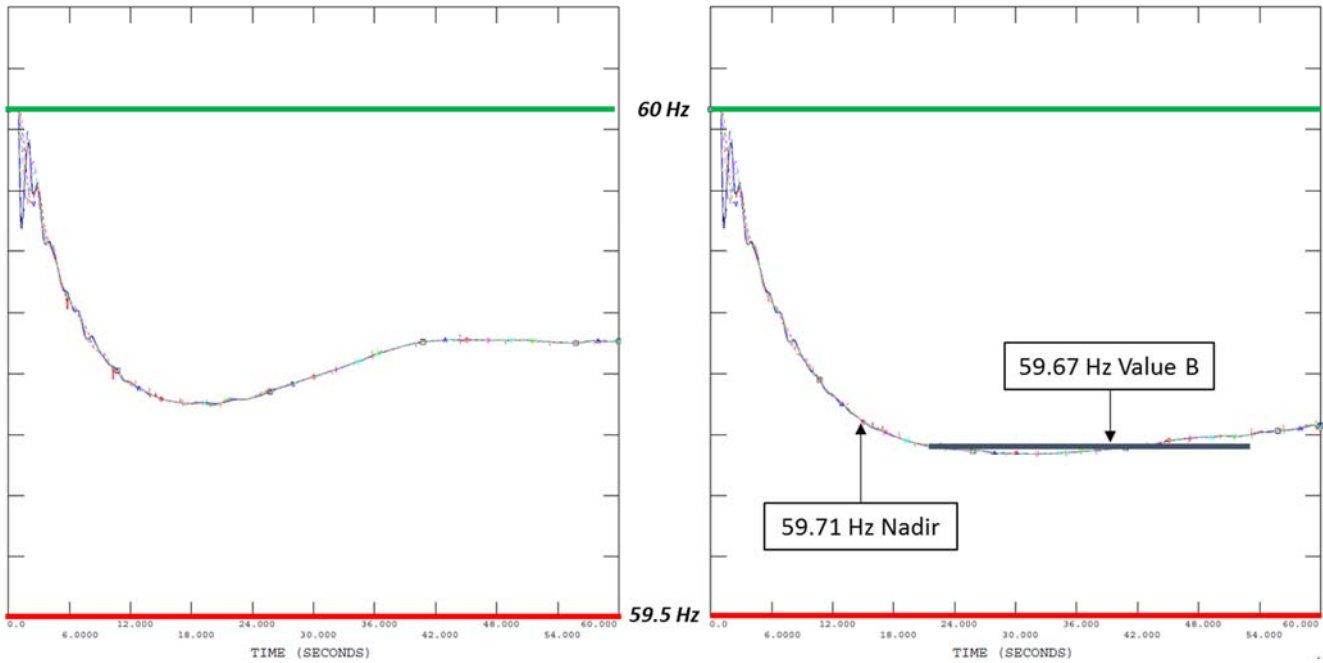
Figure 6: Eastern Interconnection Frequency Response Simulations

Western Interconnection

Dynamic simulation of the defined resource contingency as per BAL-003-1 was performed for the Western Interconnection with frequency response degraded to at least the IFRO value of 841 MW/0.1 Hz. The analysis was performed on a WECC light load near-term planning case with the following modifications:

- The interconnection-wide demand level was reduced from 105 GW to a more representative light load condition of 97 GW.
- Interchanges between areas were held constant while reducing local generation for each area uniformly based on initial demand in the case.

The adjusted WECC case, for the resource loss contingency, gives the response as shown in Figure 7. As the figure shows, frequency response is well above the first stage of UFLS at 59.5 Hz, and with an interconnection frequency response measure (FRM) of 2,119 MW/0.1 Hz. The mean frequency has been used to obtain the representative points shown in the figure.
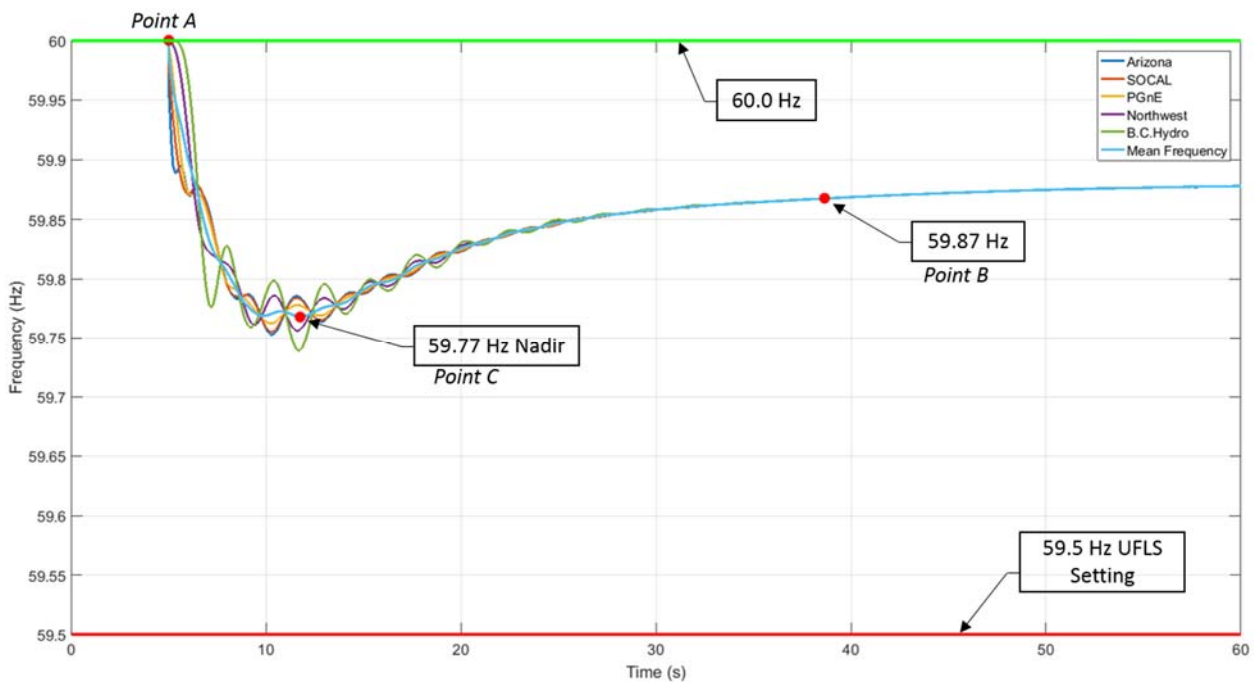
Figure 7: WECC Starting Case Simulation

Frequency response was degraded from this case to a worst case scenario for the West of a response at the IFRO value of around 841 MW/0.1 Hz. This was accomplished by baseloading the majority of generation in certain areas, particularly Southern California and Arizona. Figure 8 shows the response for this case. The CB_R ratio in the simulation is relatively close to the statistically determined CB_R ratio from historical performance.
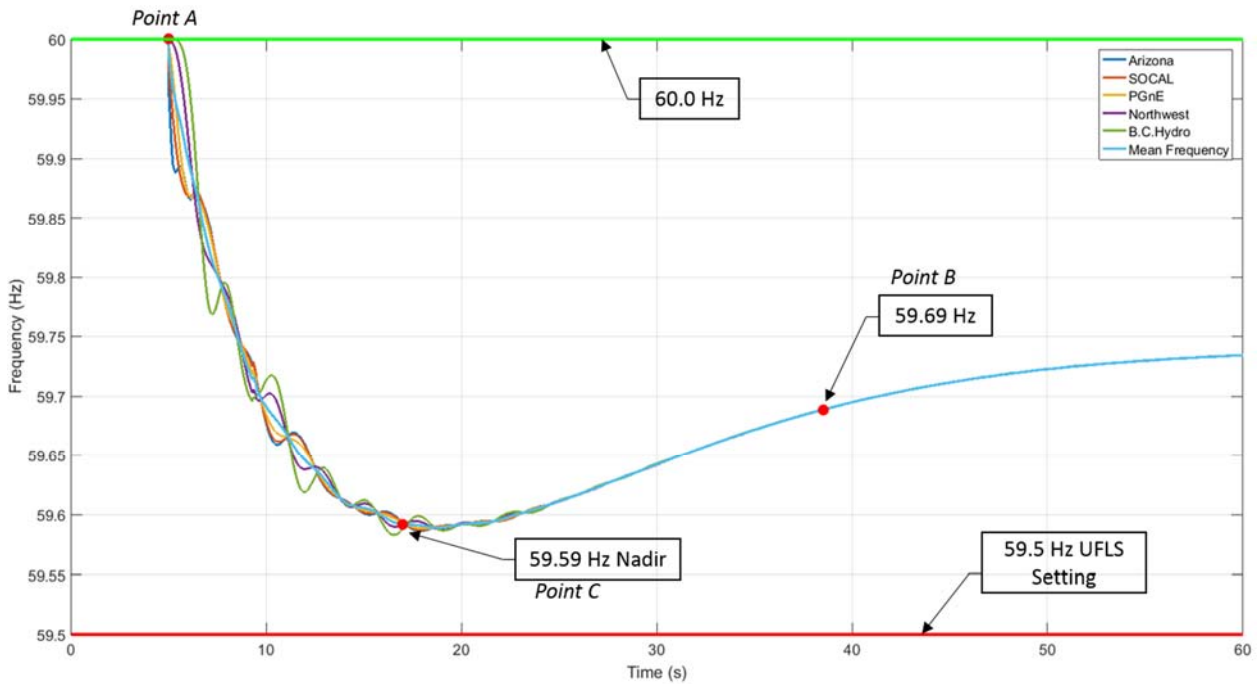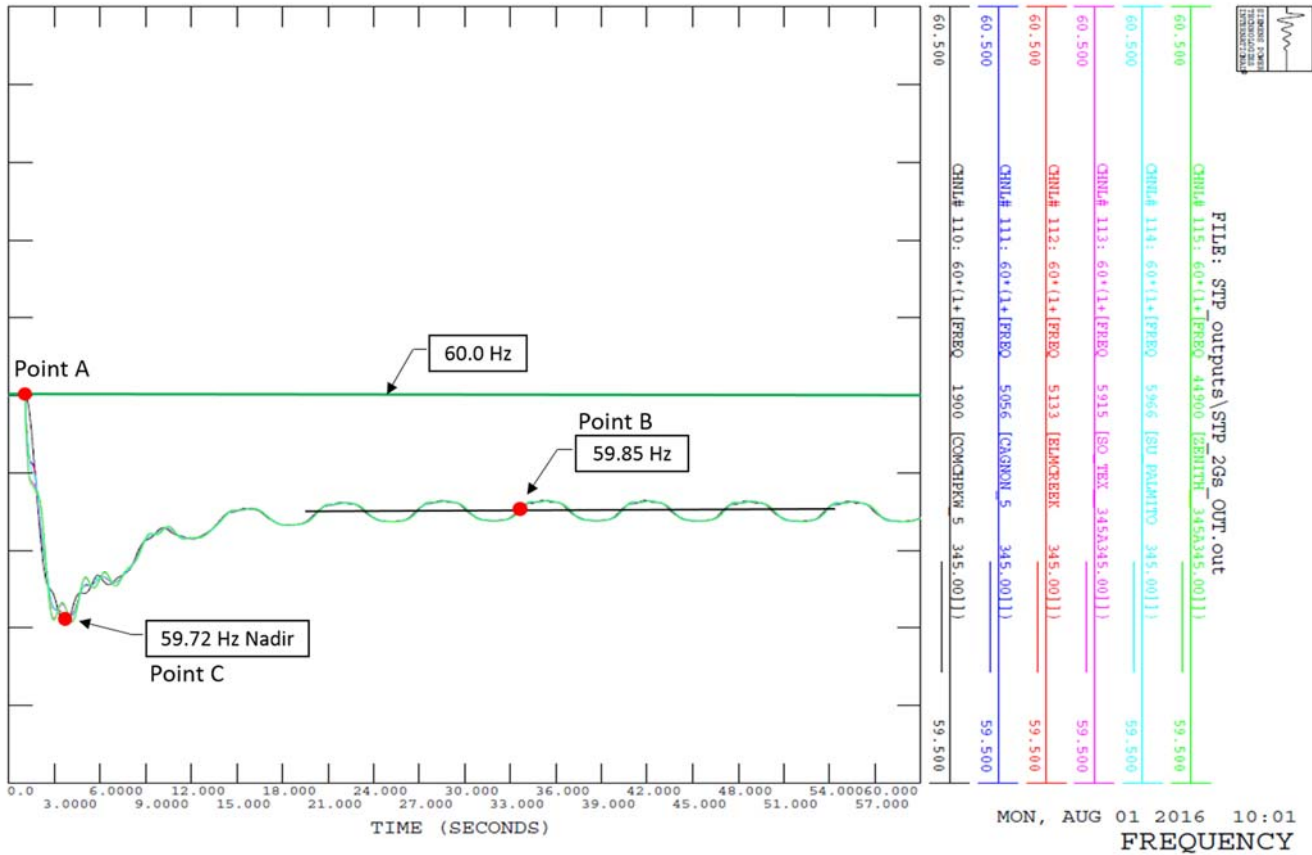
Figure 8: Western Interconnection Frequency Response Simulation

With a frequency response characteristic close to historical performance in the Western Interconnection the frequency nadir, for the defined resource loss protection criteria with response drastically degraded to obtain a FRM equal to the determined IFRO of 841 MW/0.1 Hz, remains above the first stage UFLS at 59.5 Hz.
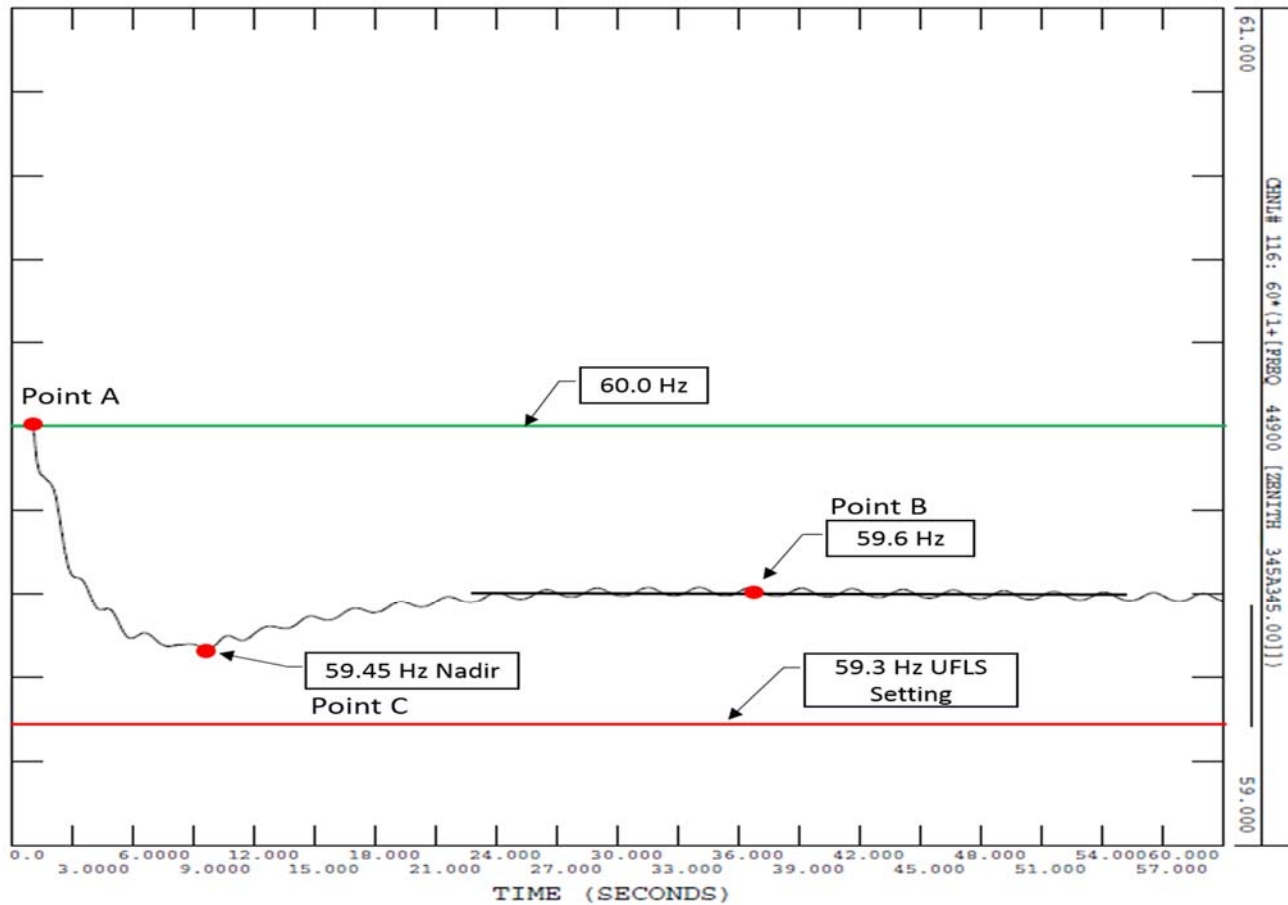
Texas Interconnection

For Texas Interconnection, the 2018 light load high wind case was used. Figure 9 shows the frequency response of the case as-is. It can be seen that the frequency response is well above the first stage of UFLS at 59.3 Hz, and with an interconnection frequency response measure (FRM) of 1,833 MW/0.1 Hz. This case exhibited abnormal oscillatory behavior likely due to dynamics modeling issues; it is recommended that ERCOT and Texas RE investigate the cause of this simulation response in the post contingency steady state timeframe of the simulation and correct any issues identified.

Figure 9: Texas Interconnection Starting Case Simulation

Frequency response was degraded from this case to a worst case scenario for a response at the IFRO value of around 380 MW/0.1 Hz. This was accomplished by switching off many of the governors arbitrarily on units across the interconnection (as for other interconnections' worst case simulations). Figure 10 shows the response for this case. The CB_R ratio in the simulation is relatively close to the statistically determined CB_R ratio from historical performance.
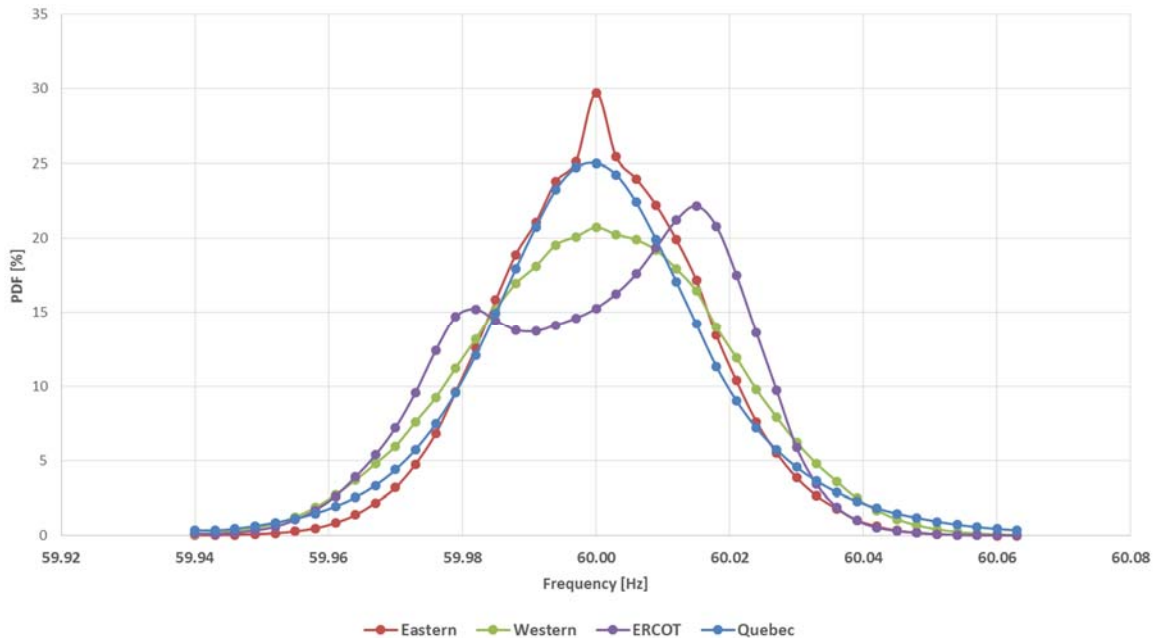
Figure 10: Texas Interconnection Frequency Response Simulation

With a frequency response characteristic close to historical performance in Texas Interconnection, the frequency nadir for the defined resource loss protection criteria with response drastically degraded to obtain a FRM equal to the determined IFRO of around 380 MW/0.1 Hz, remains above the first stage UFLS at 59.3 Hz. It can be seen that the post contingency steady state oscillatory behavior still exists as it did in the root case obtained from ERCOT.

Appendix A: Interconnection Frequency Profiles

Figure A1 shows the probability density function (PDF) for each interconnection for the years analyzed (2012 through 2015). The PDFs for the Eastern, Western, and Quebec Interconnections are consistent with previous years' analysis; however, the Texas Interconnection PDF has changed particularly due to the 2015 distribution.
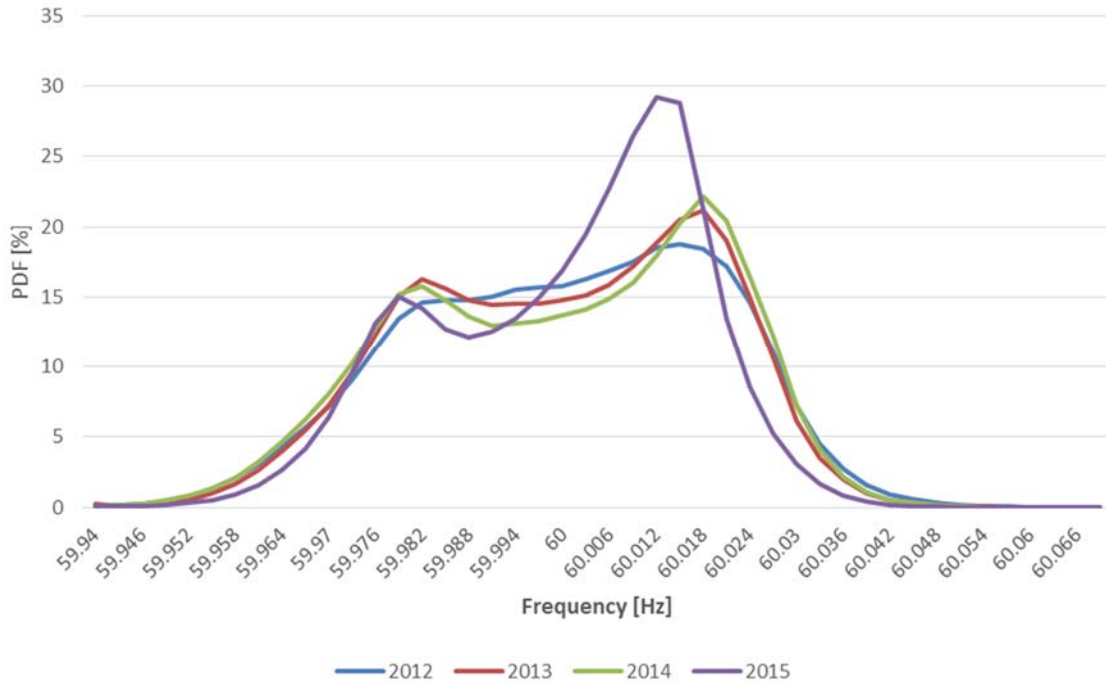

Figure A1: Probability Density Functions by Interconnection 2012-2015 Data

Figure A2 shows the PDF by year (2012 through 2015) for Texas Interconnection. It is clear that the frequency profile in 2015 is significantly different than the profiles for previous years. This can be attributed to implementation of the BAL-001-TRE-1. The right side tail of the PDF has moved closer to nominal 60 Hz, with a predominant peak near 60.017. This is consistent with BAL-001-TRE-1 Requirement R6.1, requiring governor deadbands for steam and hydro turbines with mechanical governors have a deadband setting within +/- 0.034 Hz and all other generating units/generating facilities to have a deadband setting within +/- 0.017 Hz. With the majority of new generation coming online in the ERCOT region being wind and natural gas resources, these facilities will have deadband settings of +/- 0.017 Hz.

It is clear from these observations that the BAL-001-TRE-1 standard has resulted in tighter frequency control. The PDF distinctly shows the impact of wind frequency response and deadband settings moving the right side inward and increasing the amount of time spent inside the 0.017 Hz upper deadband for those resources.

Analysis of frequency response for Texas Interconnection events in 2015 and early 2016 show a general improvement over that for 2013 and 2014. It was postulated that primary frequency response may improve when above the 60.017 Hz deadband due to the curtailed resources. However, examination of frequency events that start at or above the deadband was inconclusive. Since the sample was very small, further review is warranted in next year's FRAA.

Figure A2: Texas Probability Density Function for Years 2012-2015

The Quebec Interconnection has a consistent year-to-year change in the frequency PDF. The change indicates growing spread of frequency values, which is also confirmed by increasing standard deviation of annual samples. This implies that in the Quebec Interconnection, frequency variability is increasing.
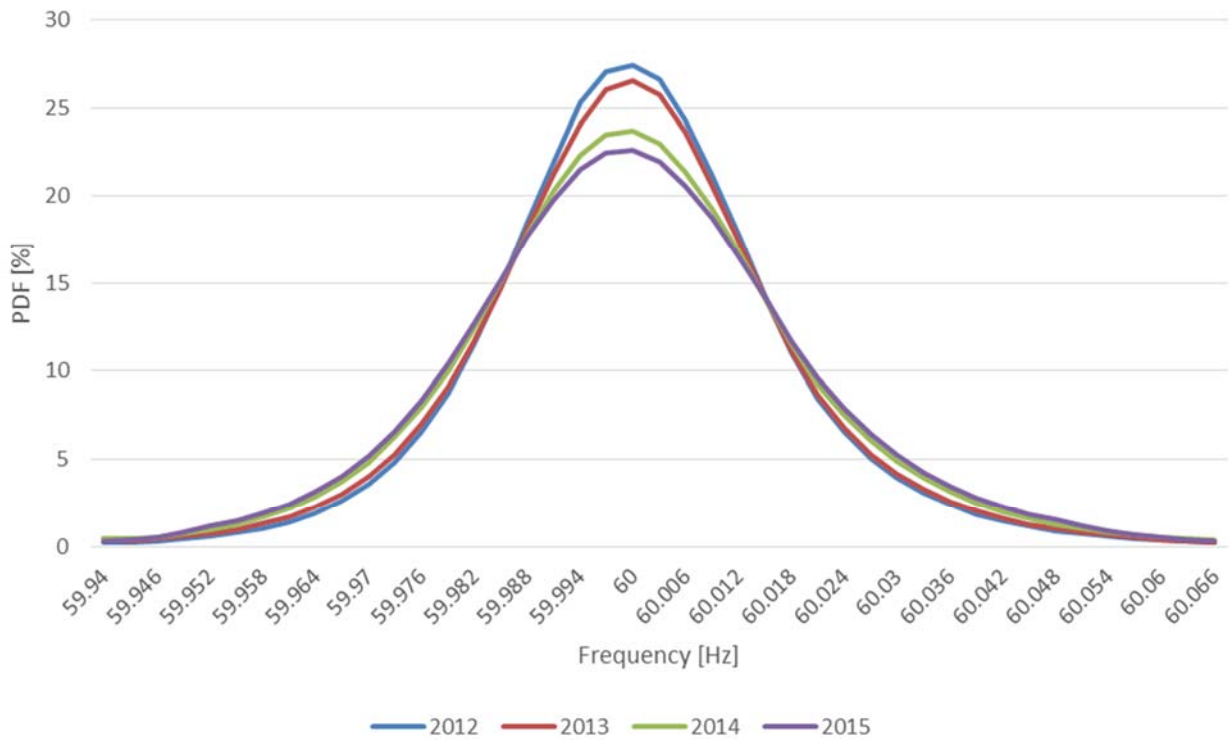
Figure A3: Quebec Probability Density Function for Years 2012-2015