2021 Frequency Response Annual Analysis

December 2021

This report was approved by the Resources Subcommittee on November 10, 2021.

This report was endorsed by the Reliability and Security Technical Committee (RSTC) on December 14, 2021.

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3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

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Preface

Electricity is a key component of the fabric of modern society and the Electric Reliability Organization (ERO) Enterprise serves to strengthen that fabric. The vision for the ERO Enterprise, which is comprised of the North American Electric Reliability Corporation (NERC) and the six Regional Entities (REs), is a highly reliable and secure North American bulk power system (BPS). Our mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid.

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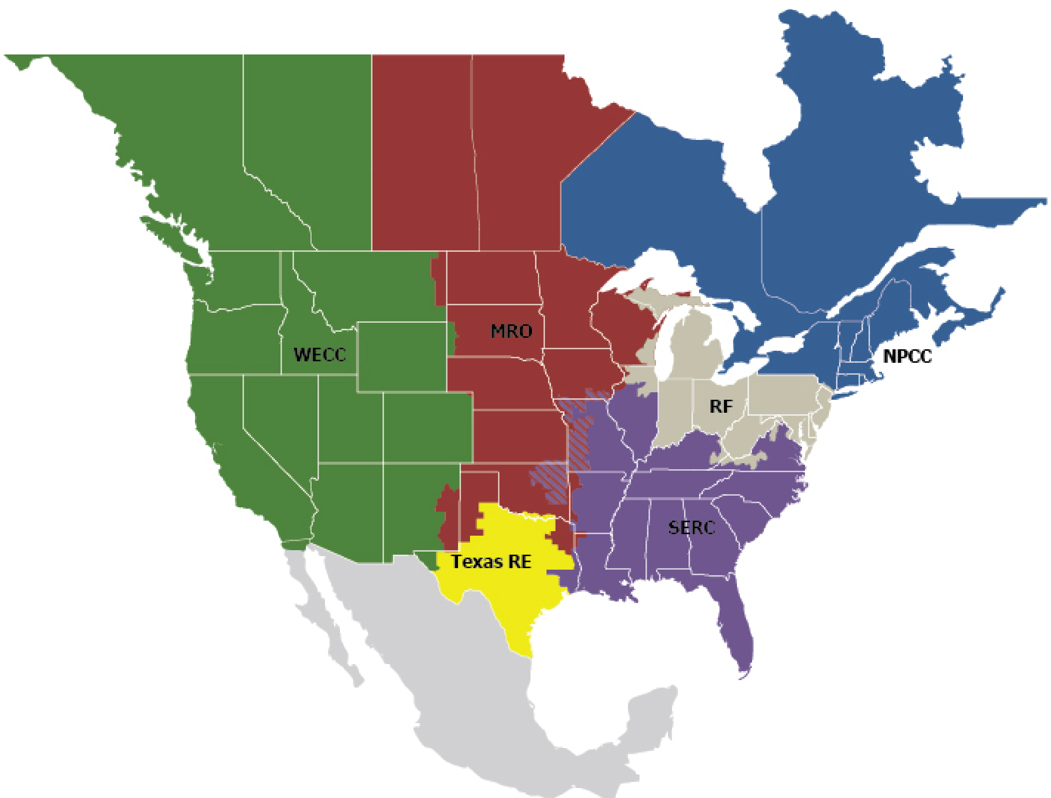
Because nearly 400 million citizens in North America are counting on us

The North American BPS is made up of six RE boundaries as shown in the map and corresponding table below. The multicolored area denotes overlap as some load-serving entities participate in one RE while associated Transmission Owners/Operators participate in another.



MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
Texas RE	Texas Reliability Entity
WECC	WECC

Executive Summary

This report is the 2021 annual analysis of frequency response performance for the administration and support of *NERC Reliability Standard BAL-003-2 – Frequency Response and Frequency Bias Setting,*[1] effective December 1, 2020. BAL-003-2 (Phase I) revises the BAL-003-1.1 standard and process documents to include (in part) the addressing of the inconsistencies in calculation of Interconnection frequency response obligations (IFRO) due to interconnection frequency response performance changes of Point C and/or Value B; the Eastern Interconnection (EI) Resource Contingency Protection Criteria; and the frequency of nadir point limitations (prior limited to t_0 to t_{+12}).

The *2016 FRAA* stated that 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 was addressed as part of the revision of the IFRO calculation in the BAL-003-2 Reliability Standard.

This report provides an update to the statistical analyses and calculations contained in the *2012 Frequency Response Initiative Report*[2] that was approved by the NERC Resources Subcommittee (RS), the technical committee that predated the Reliability and Security Technical Committee (RSTC), and accepted by the NERC Board of Trustees (Board). It is a transition report that includes some of the information from past IFRO method while fully supporting BAL-003-2 (phase I) requirements and looking ahead to further phased revisions.

This report is prepared by NERC staff[3] and contains the annual analysis, calculation, and recommendations for the IFRO for each of the four Interconnections of North America for the operating year (OY) 2022 (December 2021 through November 2022). Below are the key findings and recommendations contained in this report.

This report further includes **Appendix A**, which details the performance of respective interconnections in arresting frequency reduction for loss of generation events, most commonly referenced as Point A–C analysis. This analysis is specifically concerned with maintaining margin between the lowest event frequency and the first-level of underfrequency load shed scheme. NERC formerly presented this analysis in the annual State of Reliability report.

Key Findings

Continued Increase in CB_R Supports Changes to IFRO Calculation Effected in BAL-003-2

The ratio between CB_R is a multiplicative factor in the IFRO formulae that couples these two quantities together in the formulation of the IFRO. The original intent of the IFRO calculation was to ensure that a declining frequency nadir (as demonstrated by an increasing A–C) would result in an increase in the IFRO. However, the calculation also resulted in an increase in IFRO when Stabilizing Period performance improved (as demonstrated by a decreasing A–B) while Point C remained relatively stable when performing calculations to meet BAL-003-1. When CB_R increased and all other variables remained the same, the IFRO increased when using that calculation method. The IFRO should not penalize an Interconnection for improved performance of Value B during the Stabilizing Period. **Table 2.7** shows the year-over-year comparison of adjusted CB_R for all Interconnections and demonstrates the trend of higher CB_R values that have resulted in higher calculated IFROs. Future iterations of this report will trend BAL-003-2 calculation improvement impacts.

Table 2.8 shows a comparison of mean Value A, mean Value B, and mean Point C that is illustrative of Interconnection performance during low frequency events over the previous OY and as compared to the 2016 OY, during which the IFRO values were frozen until OY 2022. Loss of load events have been excluded from the data in **Table 2.6**. The EI and

[1] http://www.nerc.com/pa/Stand/Reliability%20Standards/BAL-003-2.pdf

[2] http://www.nerc.com/docs/pc/FRI_Report_10-30-12_Master_w-appendices.pdf

[3] Prepared by the NERC Standards and Engineering organization.

WI maintained a trend of a mean increase in Value B and a mean decrease in A–B, indicating improved performance during the Stabilizing Period of frequency events (**Table 2.8**). The Texas Interconnection (TI) showed no change in mean Value B and mean A–B, and the Québec Interconnection (QI) had a decrease in mean Value B and increase in mean (A-B). The EI and WI show an increase or no change in mean Point C as well as a decrease or no change in mean (A–C), indicating improved performance during the Arresting Period of frequency events. This performance data demonstrates that the increases in year-over-year CB_R that result in higher calculated IFROs are due to improved Stabilizing Period performance and not due to a decline in the performance of the Point C nadir. Between OY 2020 and OY 2021, the TI and QI showed a decreasing mean Point C and increasing mean A–C.

Resource Loss Protection Criteria Method Mitigates BPS Risk

The IFRO for each Interconnection is calculated for this report by using the respective BAL-003-2 RLPC actual value derived from 2021 Form 1, BA submissions from the Interconnection:

$$\text{IFRO} = \frac{(\text{RLPC-CLR})}{(\text{MDF*10})} \text{ expressed as MW/0.1Hz,}$$

RLPC is a major determining factor in the calculated IFRO. **Table ES.1** reflects the respective changes in Interconnection RLPC as BAL-003-2 improved IFRO calculation through use of N-2 resource loss versus BAL-003-1 use of N-1 resource loss. The change in the method of determining Resource Loss Protection Criteria (RLPC) in accordance with BAL-003-2 provides greater accuracy in determining IFRO values that will mitigate risk to the BPS.

Table ES.1: Comparison of Respective RLPCs for OY 2022

Method	Eastern (EI)	Western (WI)	Texas (TI)	Québec (QI)	Units
Under BAL-003-1	4,500	2,626	2,805	1,700	MW
Under BAL-003-2 (estimated by SDT)	3,209	2,850	2,750	2,000	MW
Under BAL-003-2 (actual reported by BAs for this report)	3,740	3,069	2,805	2,000	MW

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Recommendation

NERC provides the following recommendation for the administration of *Standard BAL-003-2*[1] for OY 2022 (December 1, 2021, through November 30, 2022).

NERC requests that the recommended IFRO values calculated in this report in accordance with BAL-003-2 and shown in **Table ES.2** be approved for implementation in the OY 2022. NERC, in collaboration with the RS, shall continue to monitor and evaluate the impacts on BPS reliability as a result of changes in IFRO values.

Table ES.2: Recommended IFROs for OY 2022

Value	Eastern (EI)	Western (WI)	Texas (TI)	Québec (QI)	Units
MDF[4]	0.420	0.280	0.405	0.947	Hz
RLPC[5]	3,740	3,069	2,805	2,000	MW
CLR	0	0	1136	0	MW
Calculated IFRO	-890	-1,096	-412	-211	MW/0.1 Hz
Recommended IFROs[6]	-915	-1,096	-412	-211	MW/0.1 Hz

[4] The Procedure for ERO Support of Frequency Response and Frequency Bias Setting Standard, Version II, provided in the approved ballot for BAL-003-2, specifies that "MDF is the Maximum Delta Frequency for the specific interconnection as determined in the 2017 Frequency Response Annual Analysis (FRAA)".

[5] BAL-003-2, Attachment A specifies that RLPC be based on the two largest potential resource losses in an Interconnection. This value is required to be evaluated annually.

[6] BAL-003-2 requires that the EI IFRO will be stepped down to its calculated value over three years. The maximum reduction is limited to 100 MW/0.10 Hz annually.

Introduction

This report, prepared by NERC staff,[7] contains the annual analysis, calculation, and recommendations for the IFRO for each of the four Interconnections of North America for the OY 2022 (December 2021 through November 2022). This analysis includes the following information:

- Statistical analysis of Interconnection frequency characteristics for the OYs 2016 through 2020 (December 1, 2015, through November 30, 2020)
- Analysis of frequency profiles for each Interconnection
- Calculation of adjustment factors from BAL-003-2 frequency response events

This year's frequency response analysis builds upon the work and experience from performing such analyses since 2013. As such, there are several important things that should be noted about this report:

- The University of Tennessee–Knoxville FNET[8] data used in the analysis has seen significant improvement in data quality, 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 bandwidth filtering, least squares fit, and derivative checking.
- As with the previous year's analysis, all frequency event analysis is using subsecond data from the FNET system frequency data recorders (FDRs). This eliminates the need for the CC_{ADJ} factor originally prescribed in the *2012 Frequency Response Initiative Report*[9] because the actual frequency nadir was accurately captured.
- The frequency response analysis tool[10] is being used by the NERC Power System Analysis group for frequency event tracking in support of the NERC Frequency Working Group and RS. The tool has streamlined Interconnection frequency response analysis. The tool provides an effective means of determining frequency event performance parameters and generating a database of values necessary for calculation of adjustment factors.

This report contains numerous references to Value A, Value B, and Point C, which are defined in NERC *BAL-003-2.*[1] As such, it is important to understand the relationship between these variables and the basic tenants of primary and secondary frequency control.

The Arresting, Rebound, Stabilizing, and Recovery Periods of a frequency event following the loss of a large generation resource are shown in **Figure I.1**. Value A and Value B are average frequencies from t-16 to t-2 seconds and t+20 to t+52 seconds, respectively, as defined in NERC *BAL-003-2*. Point C is experienced within the first 20 seconds following the start of a frequency event. A Point C' value may exist if frequency falls below the original Point C nadir or Value B after the end of the 20–52 second Stabilizing Period.

[7] Prepared by the Power System Analysis and Advanced System Analytics & Modeling departments

[8] 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.

[9] http://www.nerc.com/docs/pc/FRI_Report_10-30-12_Master_w-appendices.pdf

[10] Developed by Pacific Northwest National Laboratory

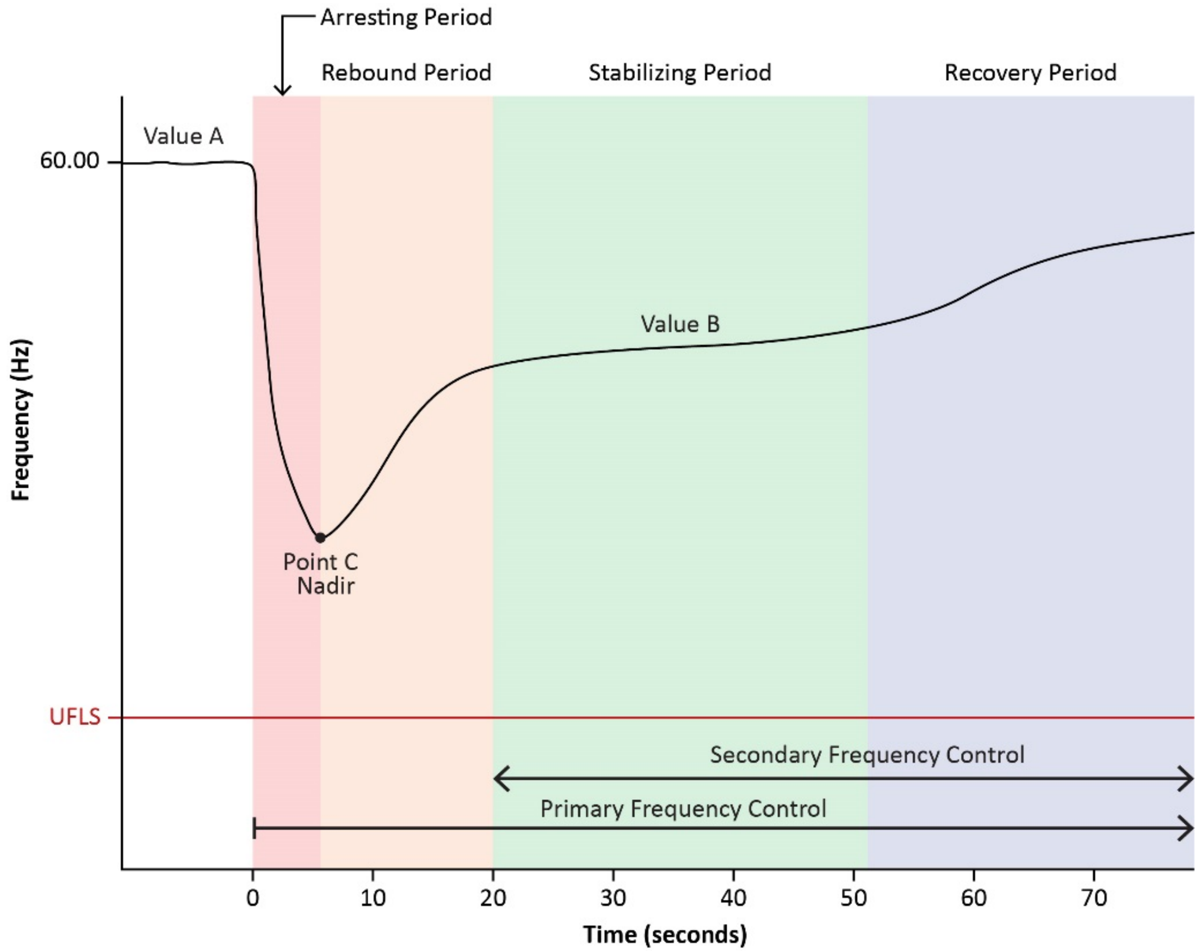

Figure I.1: Primary and Secondary Frequency Control

Primary Frequency Control: This is the action by the Interconnection to arrest and stabilize frequency in response to frequency deviations and has three time components: the Arresting Period, Rebound Period, and Stabilizing Period. These terms are defined as follows:

- **Arresting Period:** This is the time from zero (Value A) to the time of the nadir (Point C) and is the combination of system inertia, load damping, and the initial primary control response of resources acting together to limit the duration and magnitude of frequency change. It is essential that the decline in frequency is arrested during this period to prevent activation of automatic UFLS schemes in the Interconnection.
- **Rebound Period:** This includes the effects of governor response in sensing the change in turbine speed as frequency increases or declines, causing an adjustment to the energy input of the turbine's prime mover. This can also be impacted by end-user customer or other loads that are capable of self-curtailment due to local frequency sensing and control during frequency deviations.
- **Stabilizing Period:** This is the third component of primary frequency control following a disturbance when the frequency stabilizes following a frequency excursion. Value B represents the interconnected system frequency at the point immediately after the frequency stabilizes primarily due to governor action but before the contingent control area takes corrective automatic generation control action.

Chapter 1: Interconnection Frequency Characteristic Analysis

Annually, NERC staff performs a statistical analysis (as detailed in the *2012 Frequency Response Initiative Report)*[11] of the frequency characteristics for each of the four Interconnections. That analysis is performed to monitor the changing frequency characteristics of the Interconnections and to statistically determine each Interconnection's starting frequency for the respective IFRO calculations. For this report's analysis, one-second frequency data[12] from OYs 2016–2020 (December 1, 2015, through November 30, 2020) was used.

Frequency Variation Statistical Analysis

The 2021 frequency variation analysis was performed on one-second frequency data for 2016–2020 and is summarized in **Table 1.1**. This variability accounts for items like 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.

The starting frequency is calculated and published in this report for comparison and informational purposes. Starting frequencies are evaluated annually, and the analysis indicated no need to change the maximum delta frequency for OY 2022.

Table 1.1: Interconnection Frequency Variation Analysis 2016–2020

Value	Eastern	Western	Texas	Québec
Number of Samples	157,144,838	157,221,492	156,982,483	150,888,115
Filtered Samples (% of total)	99.6%	99.6%	99.4%	95.6%
Expected Value (Hz)	59.999	59.999	59.999	59.999
Variance of Frequency (σ^2)	0.00025	0.00033	0.00028	0.00041
Standard Deviation (σ)	0.01596	0.01806	0.01660	0.02032
50% percentile (median)[13]	59.999	59.999	60.003	59.998
Starting Frequency (F_{START}) (Hz)	**59.972**	**59.969**	**59.971**	**59.966**

The starting frequency is the fifth-percentile lower tail of samples from the statistical analysis, representing a 95% chance that frequencies will be at or above that value at the start of any frequency event. Since the starting frequencies encompass all variations in frequency, including changes to the target frequency during TECs, the need to expressly evaluate TEC as a variable in the IFRO calculation is eliminated.

Figure 1.1–Figure 1.4 show the probability density function (PDF) of frequency for each Interconnection. The vertical red line is the fifth-percentile frequency; the interconnection frequency will statistically be greater than that value 95% of the time. This value is used as the starting frequency.

[11] https://www.nerc.com/docs/pc/FRI_Report_10-30-12_Master_w-appendices.pdf
[12] 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.
[13] Note regarding the EI median frequency is as follows: with fast time error corrections the median value is around but slightly below 60 Hz; without these corrections the median would be above 60 Hz.

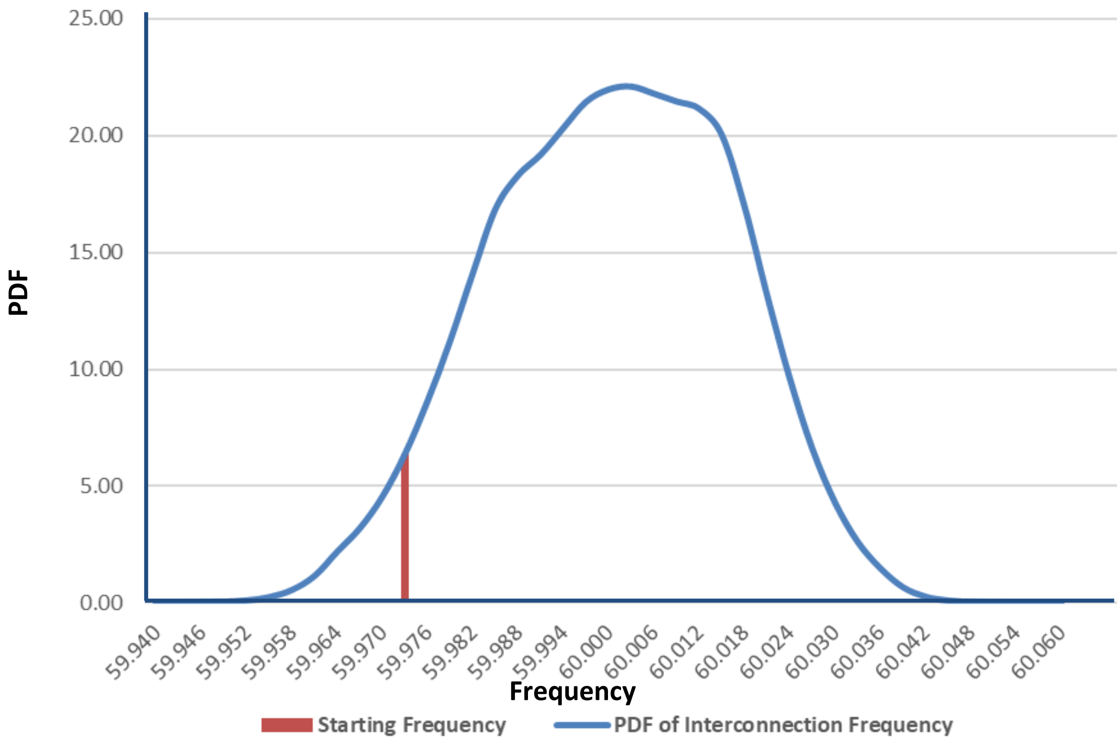

Figure 1.1: Eastern Interconnection 2016–2020 Probability Density Function of Frequency

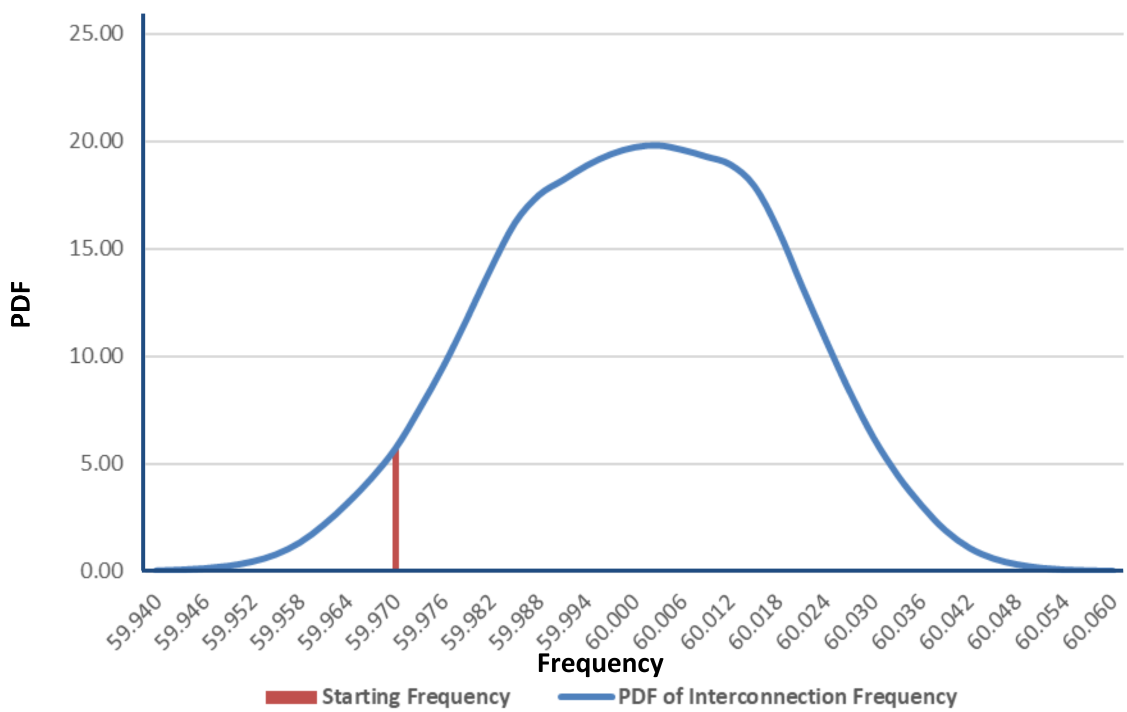

Figure 1.2: Western Interconnection 2016–2020 Probability Density Function of Frequency

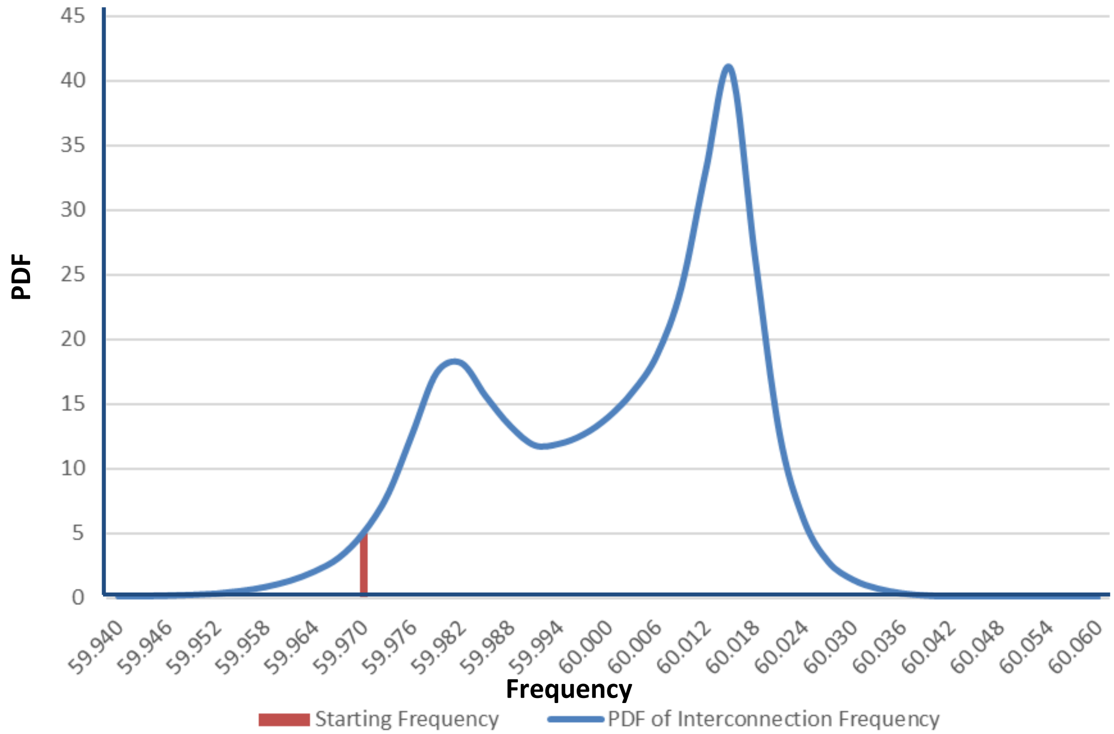

Figure 1.3: Texas Interconnection 2016–2020 Probability Density Function of Frequency

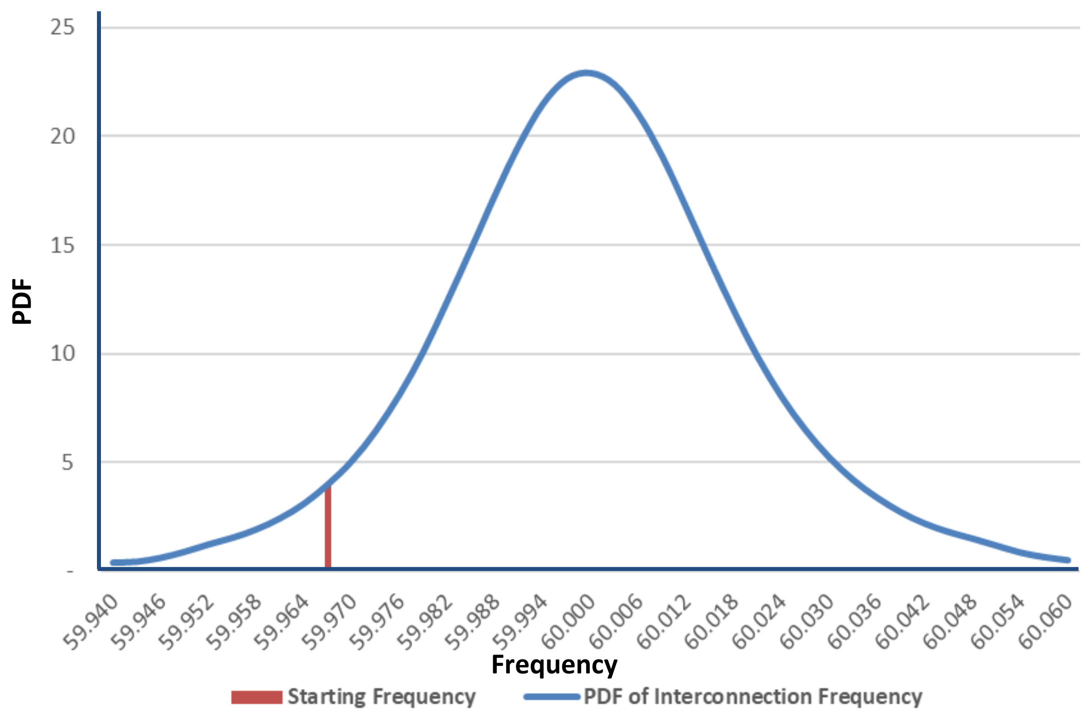

Figure 1.4: Québec Interconnection 2016–2020 Probability Density Function of Frequency

Figure 1.1–Figure 1.4 show the PDF of frequency for each Interconnection. The Interconnection frequency will statistically be greater than that value 95% of the time; this value is used as the starting frequency. Figure 1.5 shows a comparison of the PDF for all Interconnections.

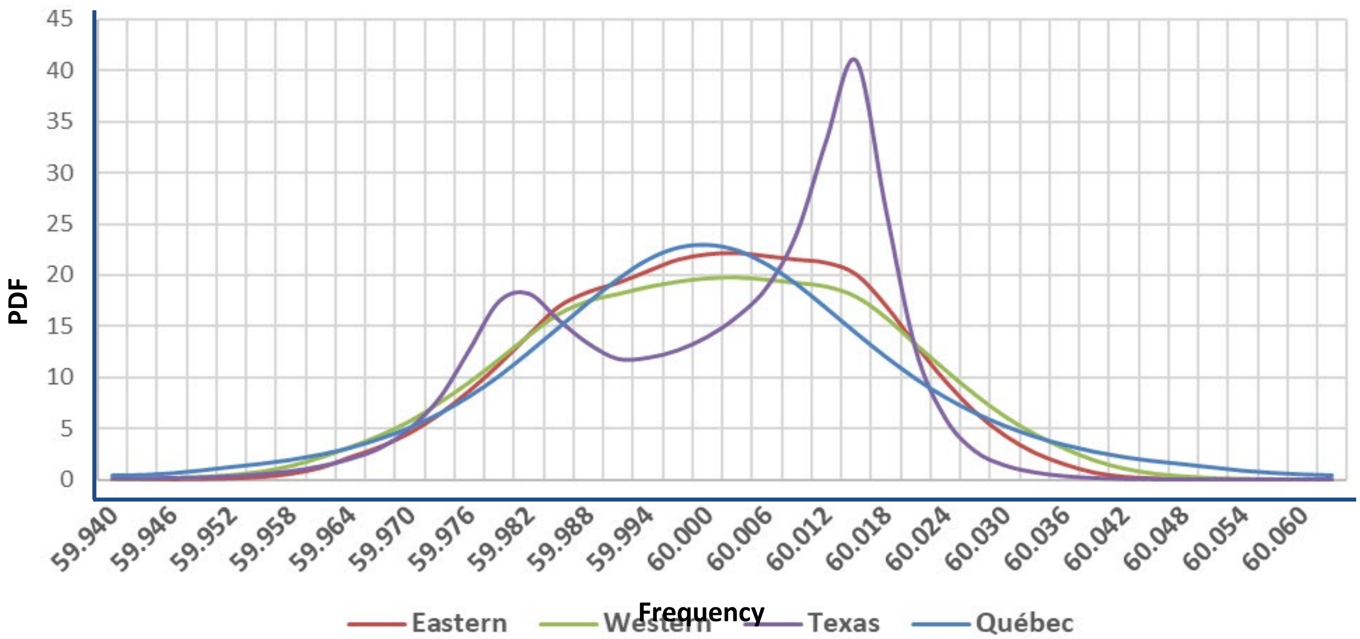

Figure 1.5: Comparison of 2016–2020 Interconnection Frequency PDFs

Variations in Probability Density Functions

The following is an analysis of the variations in probability density functions of the annual distributions of Interconnection frequency for years 2016–2020. **Table 1.2** lists the standard deviation of the annual Interconnection frequencies.

Table 1.2: Interconnection Standard Deviation by Year					
Interconnection	**2016**	**2017**	**2018**	**2019**	**2020**
Eastern	0.0157	0.0156	0.0161	0.0162	0.0163
Western	0.0190	0.0186	0.0186	0.0174	0.0176
Texas	0.0165	0.0165	0.0162	0.0165	0.0174
Québec	0.0203	0.0198	0.0203	0.0204	0.0208

In the EI, the standard deviation continued to increase in 2020 compared to 2016–2019. The standard deviation increased as well in the QI and the TI and increased slightly the WI in 2020 compared to 2019. As standard deviation is a measure of dispersion of values around the mean value, the increasing standard deviations indicate reduced concentration around the mean value and less stable performance of the interconnection frequency. Comparisons of annual frequency profiles for each Interconnection are shown in **Figure 1.6**–**Figure 1.9.**

Eastern Interconnection Frequency Characteristic Changes

The increase in standard deviation for the EI frequency characteristic in 2020 is shown in **Figure 1.6**. Statistical skewness (S)[14] continued to increase in 2020 (S = -0.17) as compared to 2016 and 2017 (S = -0.08 and -0.08,

[14] The skewness (S) is a measure of asymmetry of a distribution. A perfectly symmetric distribution has S=0. The sign indicates where a longer tail of the distribution is. The negatively-skewed distribution has a longer left tail, and its curve leans to the opposite direction (to the right). Algebraically, it means that the frequency values that are smaller than its mean are spread farther from the mean than the values greater than the mean or that there is more variability in lower values of the frequency than in higher values of the frequency.

respectively). NERC, in coordination with its technical committees, continues to evaluate this phenomenon and its impact (if any) on BPS reliability.

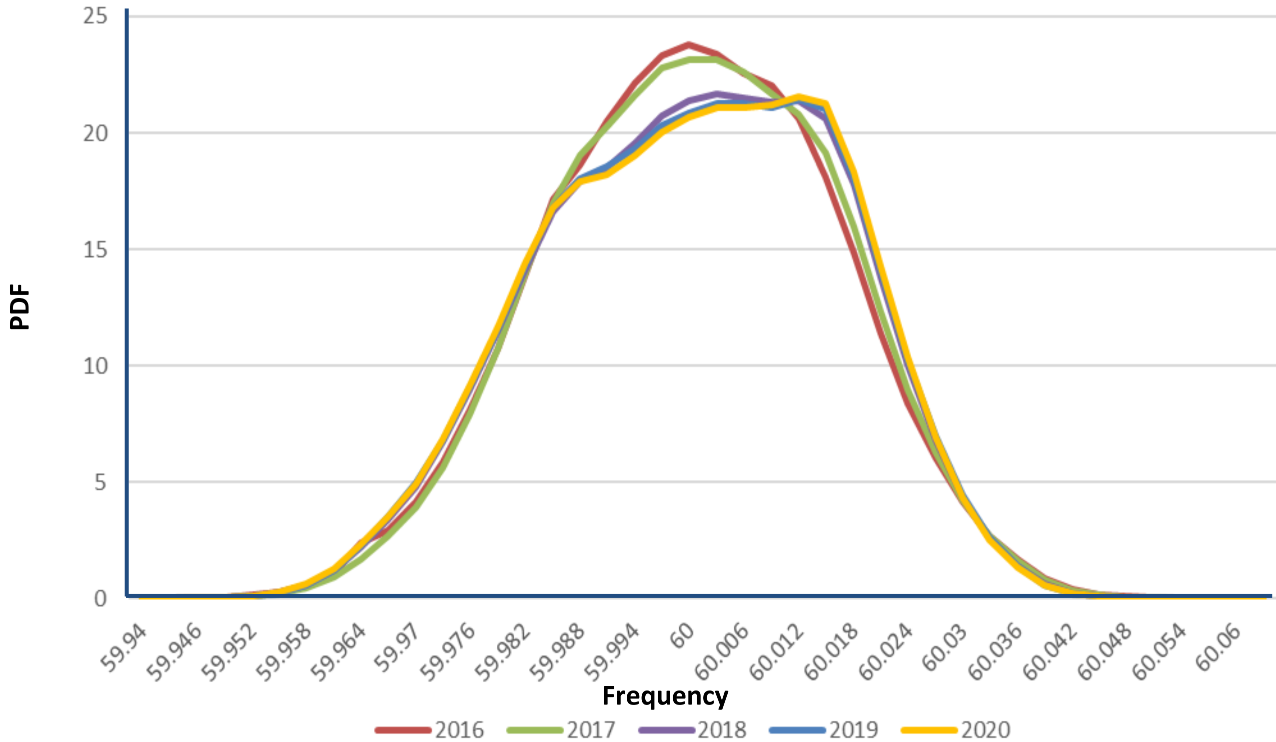

Figure 1.6: Eastern Interconnection Frequency Probability Density Function by Year

Western Interconnection Frequency Characteristic Changes

There was an observable change in the frequency distribution for the WI in 2020 that includes some skewness, as shown in **Figure 1.7**.

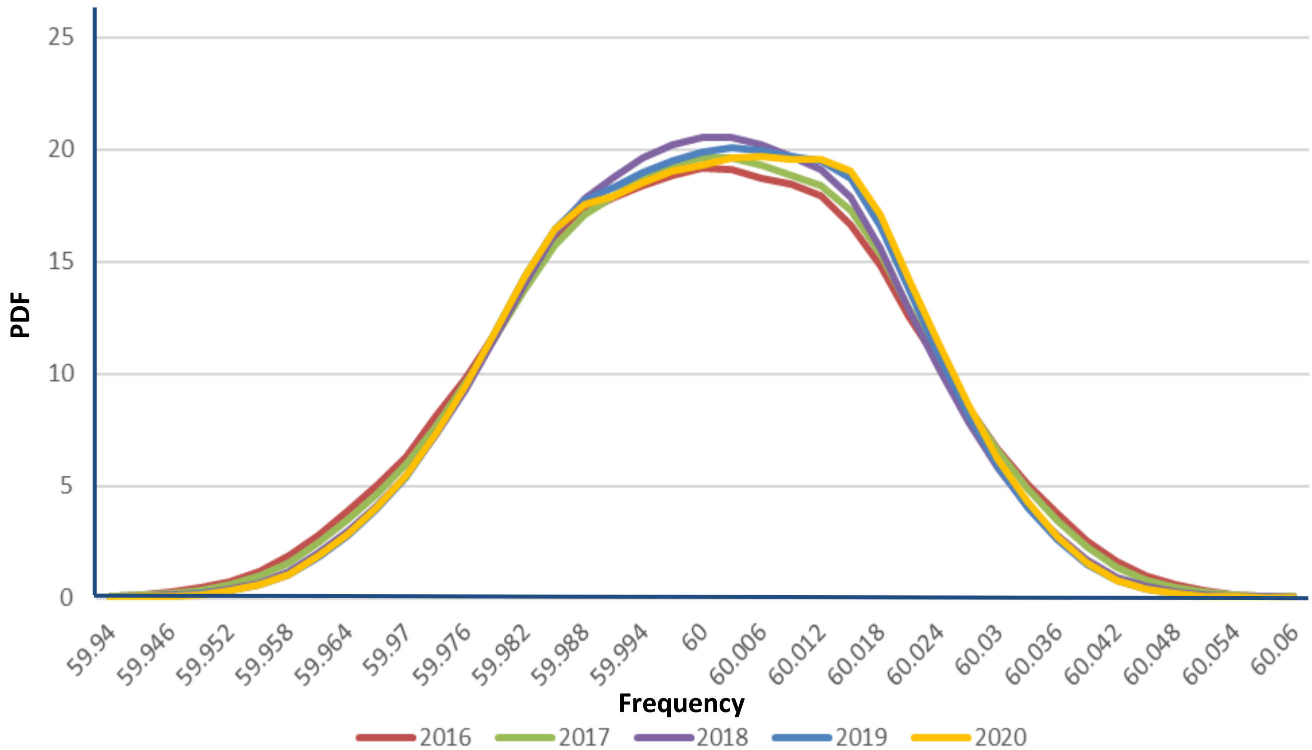

Figure 1.7: Western Interconnection Frequency Probability Density Function by Year

Texas Interconnection Frequency Characteristic Changes

Standard TRE BAL-001[15] went into full effect in April 2015 and caused a dramatic change in the probability density function of frequency for ERCOT in 2015 and 2016. This standard requires all resources in ERCOT to provide proportional nonstep primary frequency response with a ±17 mHz dead-band. As a result, when any time frequency exceeds 60.017 Hz, resources automatically curtail themselves. That has resulted in far less operation in frequencies above the dead-band since all resources, including wind, are backing down. It is exhibited in **Figure 1.8** as a probability concentration around 60.017 Hz. Similar behavior is not exhibited at the low dead-band of 59.983 Hz because most wind resources are operated at maximum output and cannot increase output when frequency falls below the dead-band.

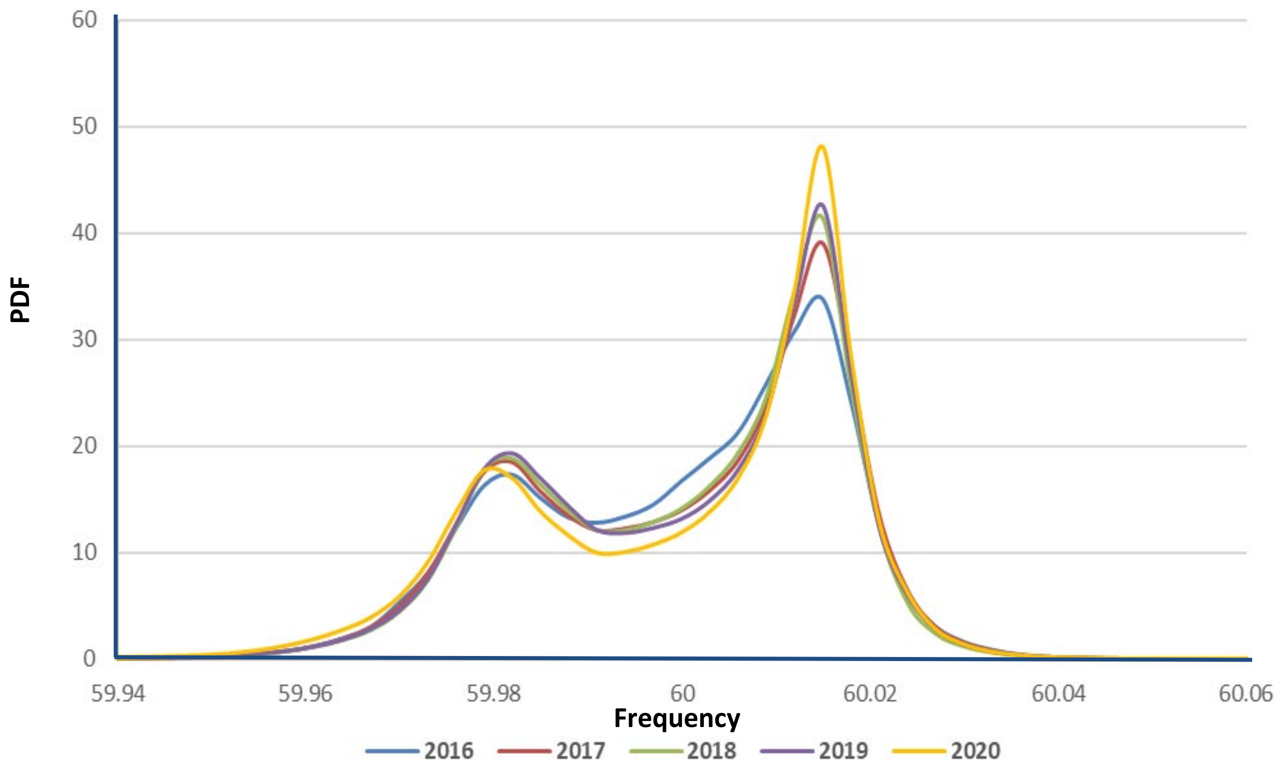

Figure 1.8: Texas Interconnection Frequency Probability Density Function by Year

[15] http://www.nerc.com/pa/Stand/Reliability%20Standards/BAL-001-TRE-1.pdf

Québec Interconnection Frequency Characteristic Changes

There were no observable changes in the shape of the distribution for the QI as shown in **Figure 1.9**.

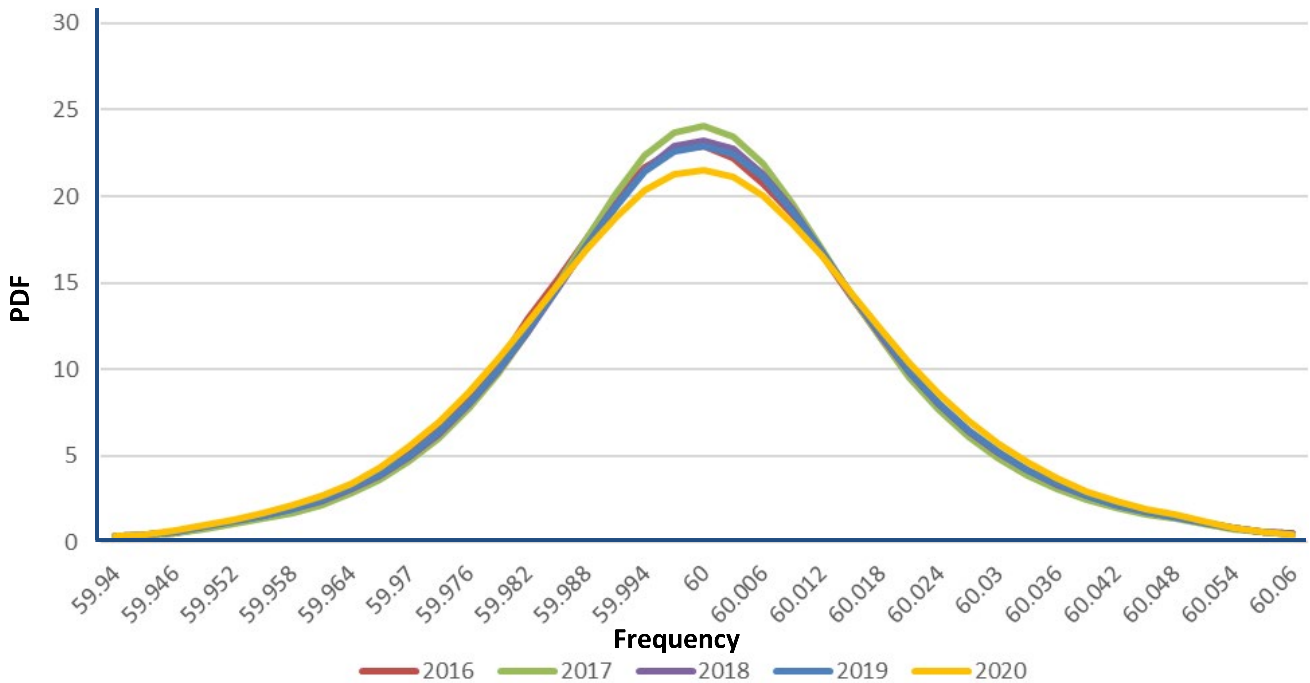

Figure 1.9: Québec Interconnection Frequency Probability Density Function by Year

Chapter 2: Determination of Interconnection Frequency Response Obligations

With this report, the calculation of the IFROs is determined by recently approved BAL-003-2. Previously, the calculation involved a multifaceted process that employed statistical analysis of past performance; analysis of the relationships between measurements of Value A, Point C, and Value B; and other adjustments to the allowable frequency deviations and resource losses used to determine the recommended IFROs. Refer to the *2012 Frequency Response Initiative Report* for additional details on the development of the IFRO and the adjustment calculation methods.[16] This report includes information that serves to transition from the old to the new method.

Tenets of IFRO

The IFRO is the minimum amount of frequency response that must be maintained by an Interconnection. Each Balancing Authority (BA) in the Interconnection is allocated a portion of the IFRO that represents its minimum annual median performance responsibility. To be sustainable, BAs 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:

- A frequency event should not activate the first stage of regionally approved UFLS systems within the Interconnection.
- Local activation of first-stage UFLS systems for severe frequency excursions, particularly those associated with delayed fault-clearing or in systems on the edge of an Interconnection, may be unavoidable.
- Other frequency-sensitive loads or electronically coupled resources may trip during such frequency events as is the case for PV inverters.
- 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 due to severe contingencies. Conceptually, that safety net should not be utilized for frequency events that are expected to happen on a relatively regular basis. As such, the resource loss protection criteria were selected in accordance with BAL-003-2 to avoid violating regionally approved UFLS settings.

Interconnection Resource Loss Protection Criteria

BAL-003-2 introduced the Interconnection RLPC to replace the Resource Contingency Protection Criteria used previously. It is based on resource loss in accordance with the following process.

NERC requests BAs to provide their two largest resource loss values and their largest resource loss due to an N-1 or N-2 RAS event. This facilitates comparison between the existing Interconnection RLPC values and the RLPC values in use. This data submission allows NERC to complete the calculation of the RLPC and IFRO.

BAs determine the two largest resource losses for the next operating year based on a review of the following items:

- The two largest balancing contingency events due to a single contingency identified by using system models in terms of loss measured by megawatt loss in a normal system configuration (N-0) (an abnormal system configuration is not used to determine the RLPC.)
  - The two largest units in the BA area, regardless of shared ownership/responsibility

[16] http://www.nerc.com/docs/pc/FRI_Report_10-30-12_Master_w-appendices.pdf

- The two largest Remedial Action Scheme (RAS) resource losses (if any) that are initiated by single (N-1) contingency events

The BA provides these two numbers determined above as Resource Loss A and Resource Loss B in the FR Form 1.

The BA should then provide the largest resource loss due to RAS operations (if any) that is initiated by a multiple contingency (N-2) event (RLPC cannot be lower than this value). If this RAS impacts more than a single BA, one BA is asked to take the lead and sum all resources lost due to the RAS event and provide that information.

The calculated RLPC should meet or exceed any credible N-2 resource loss event.

The host BA (or planned host BA) where jointly-owned resources are physically located should be the only BA to report that resource. The full ratings of the resource, not the fractional shares, should be reported.

Direct-current (dc) ties to asynchronous resources (e.g., dc ties between Interconnections, or the Manitoba Hydro Dorsey bi-pole ties to their northern asynchronous generation) should be considered as resource losses; dc lines like the Pacific DC Intertie, which ties two sections of the same synchronous Interconnection together, should not be reported. A single pole block with normal clearing in a monopole or bi-pole high-voltage dc system is a single contingency.

Calculation of IFRO Values

The IFRO is calculated using the RLPC (Table 1 from BAL-003-2):

$$\text{IFRO} = \frac{(\text{RLPC-CLR})}{(\text{MDF*10})} \text{ expressed as MW/0.1Hz}$$

As specified in the Procedure for ERO Support of Frequency Response and Frequency Bias setting Standard, "MDF is the Maximum Delta Frequency for the specific interconnection as determined in the 2017 Frequency Response Annual Analysis (FRAA)." The BAL-003-2 revision alleviated the adverse impacts of an improving CB_R.

The IFRO for each Interconnection is calculated in this report in **Table 2.5**, and it should be noted that the calculated value for the EI IFRO is estimated by BAL-003-2 to be stepped down over three years with a reduction of IFRO not to exceed -100 MW/0.10 Hz per year in accordance with BAL-003-2. Collected RLPC data exceeded the estimate at the time BAL-003-2 balloted, and EI IFRO should meet the actual calculated value in only two operating years as a result. That determines the difference between the calculated EI IFRO in **Table 2.5** and the recommended IFRO shown in **Table ES.2** and **Table 2.9**.

Determination of Adjustment Factors

The CB_R detailed in this section is no longer used in the IFRO method but is still calculated and published in this report for comparison and informational purposes.

Adjustment for Differences between Value B and Point C (CB_R)

All the calculations in 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 BA is limited to supervisory control and data acquisition (SCADA) scan rates of one to six seconds. Therefore, the ability to measure frequency response at the BA 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 selected for BAL-003-1 OYs 2015 through 2019 that capture the relationship between Value B and Point C.

Sub-Second Frequency Data Source

Frequency data used for calculating all the adjustment factors used in the IFRO calculation comes from the "FNet /GridEye system" hosted by UTK and the Oak Ridge National Laboratory. Six minutes of data is used for each frequency disturbance analyzed, one minute prior to the event and five 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 the five most perturbed FDRs for that event.

Determination of C-to-B Ratio

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 predisturbance frequency and the frequency at the maximum deviation in postdisturbance frequency (A–C) divided by the difference between the predisturbance frequency and the settled postdisturbance frequency (A–B):

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

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 shown in **Table 2.1** should be used to compensate for the differences between Point C and Value B. For this analysis, BAL-003-2 frequency events from OYs 2016–2020 (December 1, 2015, through November 30, 2020) were used.

Table 2.1: 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	125	1.159	0.177	0.026	1.185
Western	110	2.092	0.764	0.121	2.213
Texas	114	1.833	0.569	0.088	1.921
Québec	217	4.689	1.432	0.161	1.550

The EI historically exhibited a frequency response characteristic that often had Value B below Point C, and the CB_R value for the EI has been below 1.000. In those instances, the CB_R had to be limited to 1.000. However, the calculated

CB_R in this year's analysis[17] indicates a value above 1.000, so no such limitation is required. This is due in large part to the improvement made to primary frequency response of the Interconnection through the continued outreach efforts by the NERC RS and the North American Generator Forum.

The QI's resources are predominantly hydraulic and are operated to optimize efficiency, typically at about 85% of rated output. Consequently, most generators have about 15% 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 211 frequency events in their event sample, QI's CB_R value would be two to four times the CB_R values of other Interconnections. Using the same calculation method for CB_R would effectively penalize QI for their rapid rebound performance and make their IFRO artificially high. Therefore, the method for calculating the QI CB_R was modified, limiting CB_R.

The QI has an operating mandate for frequency responsive reserves to prevent tripping the 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. The QI also protects against tripping a UFLS step set at 59.0 Hz that has a 20-second time delay that protects the Interconnection 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 QI CB_R equal 1.550.

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

At times, the actual frequency event nadir 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.[18] 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 EI.

To track frequency response withdrawal in this report, the later-occurring nadir is termed Point C', which is defined as occurring after the Value B averaging period and must be lower than either Point C or Value B.

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.

The statistical analysis is performed on the events with C' value lower than Value B to determine the adjustment factor BC'_{ADJ} to account for the statistically expected Point C' value of a frequency event. These results correct for the influence of frequency response withdrawal on setting the IFRO. **Table 2.2** 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 those where C' was below Point C for OYs 2016 through 2020 (December 1, 2015, through November 30, 2020).

Table 2.2: 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	125	42	16	0.006	0.004	0.007
Western	110	70	1	N/A	N/A	N/A
Texas	114	60	1	N/A	N/A	N/A
Québec	217	35	20	-0.017	0.023	-0.008

[17] The same was true for the 2016 analysis.

[18] BAL-003-2 redefines Point C to occur within T+20 seconds.

Only the EI had a significant number of resource-loss events where C′ was below Point C or Value B for those events. The 20 events detected for QI and 1 event for WI are for load-loss events; this is indicated by the negative values for the mean difference and the BC'_{ADJ}. The adjustment is not intended to be used for load-loss events.

Although one event with C′ lower than Point C was identified in the TI, it does not warrant an adjustment factor; only the adjustment factor of 7 mHz for the EI is necessary. Of the 125 frequency events analyzed in the EI, there were 42 events that exhibited a secondary nadir where Point C′ was below Value B and 16 events where Point C′ was lower than the initial frequency nadir (Point C). These secondary nadirs occur beyond 52 seconds after the start of the event,[19] within the time frame for calculating Value B, so a BC'_{ADJ} is only needed for the EI; no BC'_{ADJ} is needed for the other three Interconnections. This will continue to be monitored moving forward to track these trends in C′ performance.

Low-Frequency Limit

The low-frequency limits to be used for the IFRO calculations (**Table 2.3**) should be the highest step in the Interconnection for regionally approved UFLS systems. These values have remained unchanged since the *2012 Frequency Response Initiative Report*.

Table 2.3: 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 EI is 59.7 Hz in SERC-Florida Peninsula (FP), which was previously FRCC, while the highest set point in the rest of the Interconnection is 59.5 Hz. The SERC-FP 59.7 Hz first UFLS step is based on internal stability concerns and is meant to prevent the separation of the FP from the rest of the Interconnection. SERC-FP concluded that the IFRO starting point of 59.5 Hz for the EI is acceptable in that it imposes no greater risk of UFLS operation for an Interconnection resource loss event than for an internal SERC-FP 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, especially in electrical proximity to faults or the loss of resources. Severe system conditions might drive the combination of frequency and voltage to levels that present some generator and turbine control systems to trip the generator. Similarly, severe rates-of-change occurring in voltage or frequency might actuate volts-per-hertz relays; this would also trip some generators, and some combustion turbines may not be able to sustain operation at frequencies below 59.5 Hz.

Inverter-based resources may also be susceptible to frequency extremes. 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, about 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 inverter-based resources.

[19] The timing of the C′ occurrence is consistent with outer-loop plant and unit controls, causing withdrawal of inverter-based resource frequency response.

Credit for Load Resources (CLR)

The TI depends on contractually interruptible (an ancillary service) demand response that automatically trips at 59.7 Hz by under-frequency relays to help arrest frequency declines. A CLR is made for the resource contingency for the TI.

The amount of CLR available at 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 2019 through December 2020, like the approach used in the *2015 FRAA* and in the *2016 FRAA*. Statistical analysis indicated that 1,136 MW of CLR is available 95% of the time. Therefore, a CLR adjustment of 1,136 MW is applied in the calculation of the TI IFRO as a reduction to the RLPC.

ERCOT Credit for Load Resources

Prior to April 2012, ERCOT was procuring 2,300 MW of responsive reserve service, of which up to 50% 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 responsive reserve service 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 automatic primary frequency response.

Determination of Maximum Allowable Delta Frequencies

Because of the measurement limitation[20] of the BA-level frequency response performance, 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 2.4 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 the following:

- Adjustments for the differences between Point C and Value B
- Adjustments for the event nadir being below Value B or Point C due to primary frequency response withdrawal measured by Point C'

Table 2.4: Determination of Maximum Allowable Delta Frequencies

Value	EI	WI	TI	QI	Units
Starting Frequency	59.972	59.969	59.971	59.966	Hz
Minimum Frequency Limit	59.500	59.500	59.300	58.500	Hz
Base Delta Frequency	0.472	0.469	0.671	1.466	Hz
CB_R[21]	1.185	2.213	1.921	1.550	Hz
Delta Frequency (DF_{CBR})[22]	0.398	0.212	0.349	0.946	Hz
BC'_{ADJ}[23]	0.007	N/A	N/A	-0.008	-
Calculated Max. Allowable Delta Frequency	0.391	0.212	0.349	0.954	Hz

[20] Due to the use of 1–6 second scan-rate data in BA's EMS systems to calculate the BA's Frequency Response Measures for frequency events under BAL-003-1

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

[22] Base Delta Frequency/CB_R

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

Table 2.4: Determination of Maximum Allowable Delta Frequencies					
Value	EI	WI	TI	QI	Units
Max. Delta Frequency Per Procedure for ERO Support of Frequency Response and Frequency Bias Setting Standard	0.420	0.280	0.405	0.947	Hz

Calculated IFROs

Table 2.5 shows the determination of IFROs for OY 2022 (December 2021 through November 2022) under standard BAL-003-2 as well as under 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 subsecond data (CC_{ADJ}), and the event nadir being below the Value B (BC'_{ADJ}).

Table 2.5: Initial Calculation of Operating Year 2022 IFROs					
Value	Eastern	Western	ERCOT	Québec	Units
Resource Loss Protection Criteria	3,740	3,069	2,805	2,000	MW
Credit for Load Resources	N/A	N/A	1136	N/A	MW
Calculated IFRO Using BAL-003-1 Method					
Starting Frequency	59.972	59.969	59.971	59.966	Hz
Calculated Max. Delta Frequency	0.391	0.212	0.349	0.954	Hz
Calculated IFRO using Calculated 2021 MDF	-957	-1096	-412	-210	
Calculated IFRO Using BAL-003-2 Method (2017 MDF)					
Max. Delta Frequency Per Procedure for ERO Support of Frequency Response and Frequency Bias Setting Standard	0.420	0.280	0.405	0.947	Hz
Calculated IFRO using 2017 MDF	-890	-1,096	-412	-211	MW/0.1 Hz
Recommended IFRO					
IFRO per Procedure for ERO Support of Frequency Response and Frequency Bias Setting Standard	-915[24]	-1096	-412	-211	MW/0.10 Hz

Comparison to Previous IFRO Values

The IFROs were first calculated and presented in the *2012 Frequency Response Initiative Report*. Table 2.6 compares the current IFROs and their key component values to those presented in the *2016 FRAA* report.

[24] EI IFRO decrease is limited to 100 MW/0.10 Hz annually from previous values. Calculated value without consideration of the limitation is -890 MW/0.10 Hz.

Table 2.5: Interconnection IFRO Comparison

Value	OY 2021 In Use[25]	OY 2021 Calc.[26]	OY 2022 Calc.[27]	2021 Calc. to 2022 Calc. Change	OY 2021 In Use to 2022 Calc. Change	Units
Eastern Interconnection						
Starting Frequency	59.974	59.973	59.972	-0.001	-0.002	Hz
Max. Allowable Delta Frequency	0.443	0.418	0.420	0.002	-0.023	Hz
Resource Loss Protection Criteria	4,500	4,500	3,740	-760	-760	MW
Credit for Load Resources	0	0	0	0	0	MW
Absolute Value of IFRO	**1,015**	**1,092**	**890**	-202	-125	MW/0.1 Hz
Western Interconnection						
Starting Frequency	59.967	59.967	59.969	0.002	0.002	Hz
Max. Allowable Delta Frequency	0.292	0.248	0.280	0.032	-0.012	Hz
Resource Loss Protection Criteria	2,626	2,626	3069	443	443	MW
Credit for Load Resources	0	120	0	-120	0	MW
Absolute Value of IFRO	858	1,010	**1,096**	86	238	MW/0.1 Hz
Texas Interconnection						
Starting Frequency	59.966	59.971	59.971	0	0.005	Hz
Max. Allowable Delta Frequency	0.411	0.377	0.405	0.028	-0.006	Hz
Resource Loss Protection Criteria	2,750	2,750	2,805	55	55	MW
Credit for Load Resources	1,181	1,209	1,136	-73	-45	MW
Absolute Value of IFRO	**381**	**409**	**412**	3	31	MW/0.1 Hz
Québec Interconnection						
Starting Frequency	59.969	59.967	59.966	-0.001	-0.003	Hz
Max. Allowable Delta Frequency	0.948	0.946	0.947	0.001	-0.001	Hz
Resource Loss Protection Criteria	1,700	1,700	2,000	300	300	MW
Credit for Load Resources	0	0	0	0	0	MW
Absolute Value of IFRO	**179**	**180**	**211**	31	32	MW/0.1 Hz

[25] Calculated in the 2015 FRAA report. Average frequency values were for OYs 2012 through 2014.
[26] Calculated in the 2019 FRAA report. Average frequency values were for OYs 2015 through 2018.
[27] Calculated in the 2020 FRAA report. Average frequency values were for OYs 2015 through 2019.

Key Findings

Continued Increase in CB_R Supports Changes to IFRO Calculation Effected in BAL-003-2

Analysis of the characteristics of the IFRO calculations in response to trends in frequency response performance have identified inconsistencies in the IFRO calculation that have been identified and discussed, beginning with the *2016 FRAA*. The following findings are important to highlight. Although BAL-003-2 has addressed these inconsistencies, and a Standard Drafting Team continues the effort further, the explanation of these inconsistencies remains in this report as a transition between methods:

> The ratio between CB_R is a multiplicative factor in the IFRO formulae that couples these two quantities together in the formulation of the IFRO. The original intent of the IFRO calculation was to ensure that a declining frequency nadir (as demonstrated by an increasing A–C) would result in an increase in the IFRO. However, the calculation also resulted in an increase in IFRO when Stabilizing Period performance improved (as demonstrated by a decreasing A–B) while Point C remained relatively stable when performing calculations to meet BAL-003-1. When CB_R increased and all other variables remained the same, the IFRO increased when using that calculation method. The IFRO should not penalize an Interconnection for improved performance of Value B during the Stabilizing Period. **Table 2.7** shows the year-over-year comparison of adjusted CB_R for the Interconnections and demonstrates the trend of higher CB_R values that have resulted in higher calculated IFROs. Future iterations of this report will trend BAL-003-2 calculation improvement impacts.

Table 2.6: Year over Year Comparison Adjusted CB_R						
Interconnection	**OY2016**	**OY2019**	**OY2020**	**OY2021**	**OY2022**	**Difference OY2022–OY2016**
Eastern	1.052	1.134	1.148	1.152	1.185	0.133
Western	1.598	1.879	2.004	2.009	2.213	0.615
Texas	1.619	1.774	1.826	1.835	1.921	0.302
Québec	1.55	1.55	1.55	1.55	1.55	0

Resource Loss Protection Criteria (RLPC)

The IFRO for each Interconnection is calculated for this report with the respective BAL-003-2 RLPC actual value derived from the BA submissions of 2021 Form 1 for each Interconnection, represented below:

$$\text{IFRO} = \frac{(\text{RLPC-CLR})}{(\text{MDF*10})} \text{ expressed as MW/0.1Hz}$$

RLPC is a major determining factor in the calculated IFRO. **Table ES.1** reflects the respective changes in Interconnection RLPC as BAL-003-2 improved IFRO calculation through use of N-2 resource loss versus BAL-003-1 use of N-1 resource loss.

Table 2.8 shows a comparison of mean Value A, mean Value B, and mean Point C that is illustrative of Interconnection performance over the previous OY and as compared to the 2016 OY when the IFRO values were frozen. Loss of load events have been excluded from the data in **Table 2.8**. The EI and WI maintained the trend of an increase in mean Value B and a decrease in the mean (A–B), indicating improved performance during the Stabilizing Period of frequency events. The TI showed no change in mean Value B and mean (A-B), and The QI had a decrease in mean Value B and increase in mean (A–B). The EI and WI show an increase or no change in mean Point C as well as a decrease or no change in mean (A–C), indicating improved performance during the Arresting Period of frequency events. This performance data demonstrates that the increases in year-over-year CB_R that result in higher calculated IFROs are due to improved Stabilizing Period performance and not due to a decline in the performance of the Point C nadir. The TI and QI showed decreasing mean Point C and increasing mean (A-C).

Table 2.7: Year over Year Comparison Value A, Value B, and Point C (Loss of Load Events Excluded)

Value	OY2016	OY2021	OY2022	Difference OY2022–OY2016	Difference OY2022–OY2021
Eastern Interconnection					
Mean Value A (Hz)	59.998	59.999	59.999	0.001	0.000
Mean Value B (Hz)	59.947	59.953	59.954	0.006	0.001
Mean Point C (Hz)	59.947	59.949	59.949	0.002	0.000
Mean A–B (Hz)	0.051	0.046	0.045	-0.005	-0.001
Mean A–C (Hz)	0.051	0.050	0.050	-0.001	0.000
Western Interconnection					
Mean Value A (Hz)	60.000	59.995	59.995	-0.005	0.000
Mean Value B (Hz)	59.923	59.934	59.936	0.011	0.002
Mean Point C (Hz)	59.887	59.887	59.890	0	0.003
Mean A–B (Hz)	0.077	0.061	0.059	-0.016	-0.002
Mean A–C (Hz)	0.112	0.108	0.105	-0.004	-0.003
Texas Interconnection					
Mean Value A (Hz)	59.996	59.997	59.997	0.001	0.000
Mean Value B (Hz)	59.889	59.918	59.918	0.029	0.000
Mean Point C (Hz)	59.840	59.865	59.863	0.025	-0.002
Mean A–B (Hz)	0.107	0.079	0.079	-0.028	0.000
Mean A–C (Hz)	0.156	0.132	0.134	-0.024	0.002
Québec Interconnection					
Mean Value A (Hz)	60.003	60.003	60.004	0	0.001
Mean Value B (Hz)	59.843	59.876	59.870	0.033	-0.006
Mean Point C (Hz)	59.433	59.533	59.522	0.1	-0.011
Mean A–B (Hz)	0.160	0.127	0.133	-0.033	0.006
Mean A–C (Hz)	0.570	0.469	0.482	-0.101	0.013

Recommended IFROs for OY 2022

Consistent with the requirements of BAL-003-2, the IFRO values shown in **Table 2.9** for OY 2022 (December 2021 through November 2022) are recommended as follows:

Table 2.8: Recommended IFROs for OY 2022					
Value	**EI**	**WI**	**TI**	**QI**	**Units**
MDF[28]	0.420	0.280	0.405	0.947	Hz
RLPC[29]	3,740	3,069	2,805	2,000	MW
CLR	0	0	1136	0	MW
Calculated IFRO	-890	-1096	-412	-211	MW/0.1 Hz
Recommended IFRO[30]	-915	-1096	-412	-211	**MW/0.1 Hz**

[28] The Procedure for ERO Support of Frequency Response and Frequency Bias Setting Standard, Version II provided in the approved ballot for BAL-003-2 specifies that “MDF is the Maximum Delta Frequency for the specific Interconnection as determined in the 2017 Frequency Response Annual Analysis (FRAA)”.

[29] BAL-003-2, Attachment A specifies that RLPC be based on the two largest potential resource losses in an interconnection. This value is required to be evaluated annually.

[30] BAL-003-2 requires that the EI IFRO will be stepped down to its calculated value over three years. The maximum reduction is limited to 915 MW/0.10 Hz annually.

Chapter 3: Dynamics Analysis of Recommended IFROs

Because the IFROs for the EI, WI, and TI have only upon issue of this report been changed as governed by BAL-003-2, additional dynamic validation analyses were not done for this report.

Refer to the dynamics validation in the *2017 FRAA*[31] report for details. No analysis was performed for the QI.

Further supporting dynamic studies accompanied the development and filing of BAL-003-2.

[31] https://www.nerc.com/comm/OC/Documents/2017_FRAA_Final_20171113.pdf

Appendix A: Statistical Analysis of A–C Frequency Response

2016–2020 Statistical Trend Summary

Interconnection	2016–2020 Statistical Time Trend
	A–C Frequency response
Eastern	Stable (Neither decreasing nor increasing)
Texas	Stable (Neither decreasing nor increasing)
Québec	Stable (Neither decreasing nor increasing)
Western	Improving (increasing)

Eastern Interconnection

Eastern IFRM (A–C): 5-Year Data and Annual Datasets

Table A.1: Descriptive Statistics for Eastern Interconnection IFRM (A–C)

Operating Year (OY)	Number of Events	Mean Frequency Response	Standard Deviation	Median	Minimum	Maximum
2016–2020	**306**	**2,137**	**625**	**2040**	**961**	**4,615**
2016	61	2,243	550	2205	1,227	3,511
2017	80	1,974	566	1,844	961	3,611
2018	74	2,217	665	2,136	1,080	3,773
2019	56	2,105	594	1,886	1,174	3,721
2020	35	2,204	776	1,982	1,136	4,615

Eastern IFRM (A–C): Annual Distributions and Year-to-Year Changes

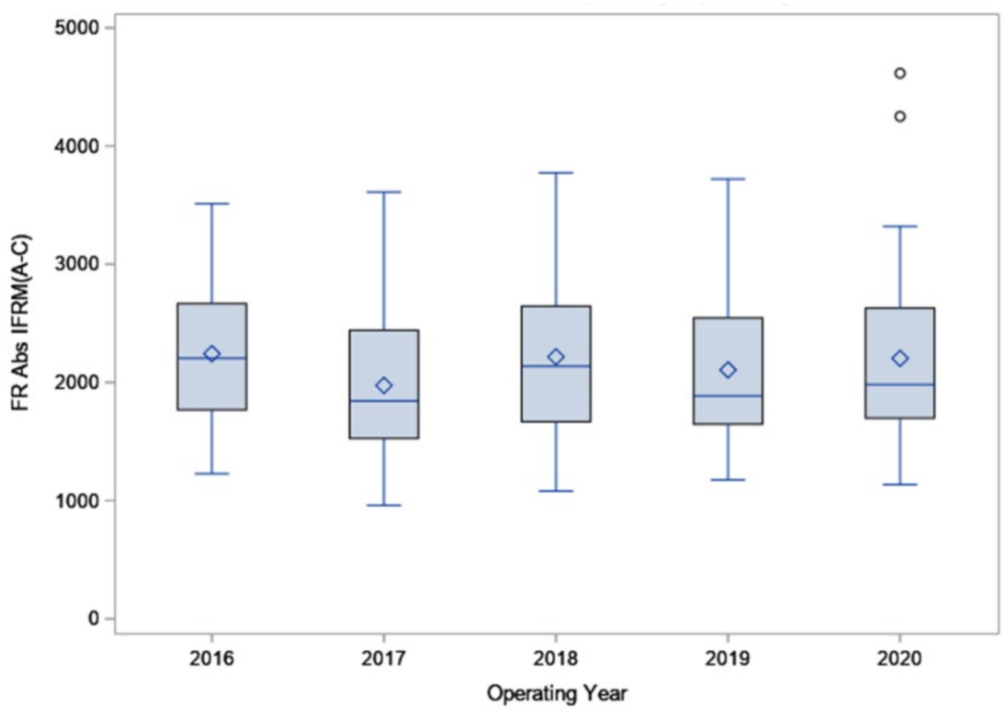

Figure A.1: Box Plots[32] of Eastern IFRM (A–C) Distribution by Operating Year 2016–2020

The 2020 mean Interconnection frequency response performance measure (IFRM) (A–C) was the third highest (and the third lowest) over the five years. Statistical tests found that the 2020 mean IFRM (A–C) was statistically similar to the other four years (in **Figure A.2** their means are connected with the 2020 mean by either a blue bar or a red bar).

[32] A box and whisker plots illustrate annual distributions as follows: The boxes enclose the interquartile range with the lower edge at the first (lower) quartile and the upper edge at the third (upper) quartile. The horizontal line drawn through a box is the second quartile or the median. The lower whisker is a line from the first quartile to the smallest data point within 1.5 interquartile ranges from the first quartile. The upper whisker is a line from the third quartile to the largest data point within 1.5 interquartile ranges from the third quartile. The data points beyond the whiskers represent outliers, or data points more than or less than 1.5 times the upper and lower quartiles, respectively. The diamonds represent the mean.

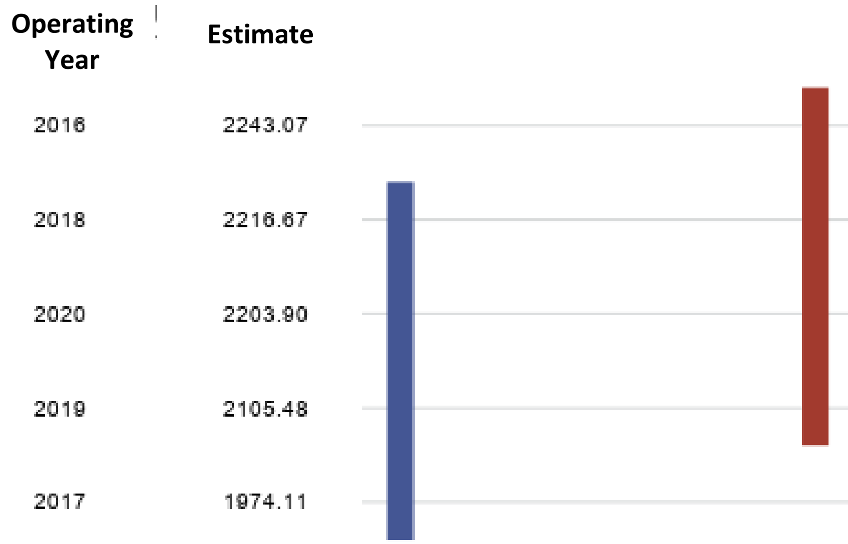

Figure A.2: Duncan Test for Eastern IFRM (A-C) Mean for Operating Years 2016–2020

Eastern IFRM (A-C): Time Trend[33]

In the EI, a linear regression line (a trend line for the IFRM (A–C) mean) shown in **Figure A.3** has a positive slope which is not statistically significant (p-value=0.96). This result implies that it is extremely likely that the positive slope of the trend line may have occurred simply by chance. This leads to the inference that from 2016–2020, the IFRM (A-C) in the EI has been neither decreasing nor increasing as measured by the mean.

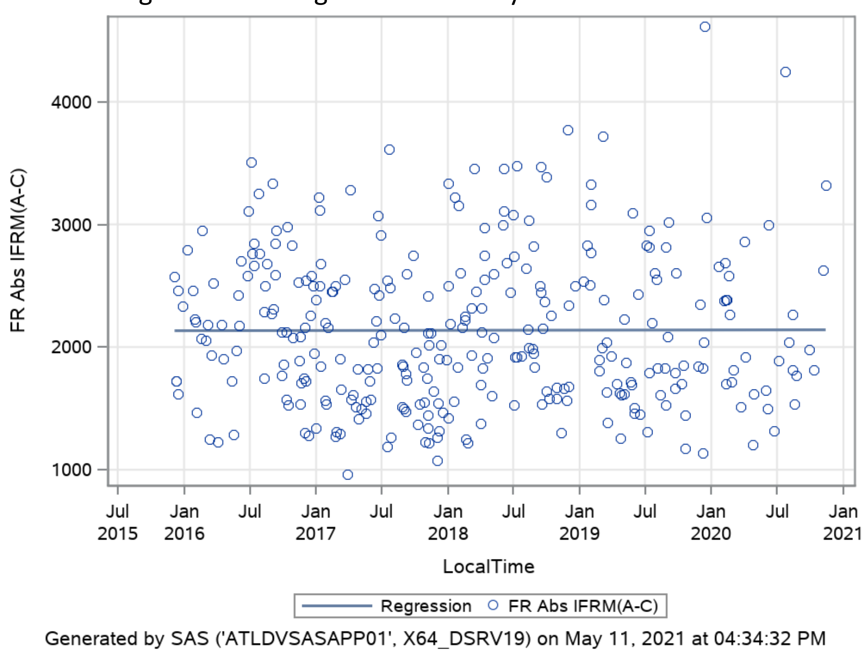

Figure A.3: Eastern IFRM (A–C) Scatter Plot and Time Trend Line for Mean IFRM (A–C) in 2016–2020

[33]The time trend analysis uses a dataset for the 2016–2020 operating years. Performance of IFRM (A-C) and its changes in time are studied by investigating relationships between IFRM (A–C) data and the explanatory variable time. A scatter plot is completed by a linear regression line that represents changes of the mean IFRM (A–C). A significance of a linear regression is tested at the significance level of 0.05. This analysis is repeated for each Interconnection.

Texas Interconnection

Texas IFRM (A–C): 5-Year Data and Annual Datasets

Table A.2: Descriptive Statistics for Texas Interconnection IFRM (A–C)

Operating Year (OY)	Number of Events	Mean Frequency Response	Standard Deviation	Median	Minimum	Maximum
2016–2020	**223**	**476**	**101**	**467**	**268**	**1,040**
2016	50	467	91	466	268	728
2017	49	452	70	455	272	585
2018	38	506	128	479	350	1,040
2019	41	495	124	492	285	872
2020	45	470	86	448	326	646

Texas IFRM (A–C): Annual Distributions and Year-to-Year Changes

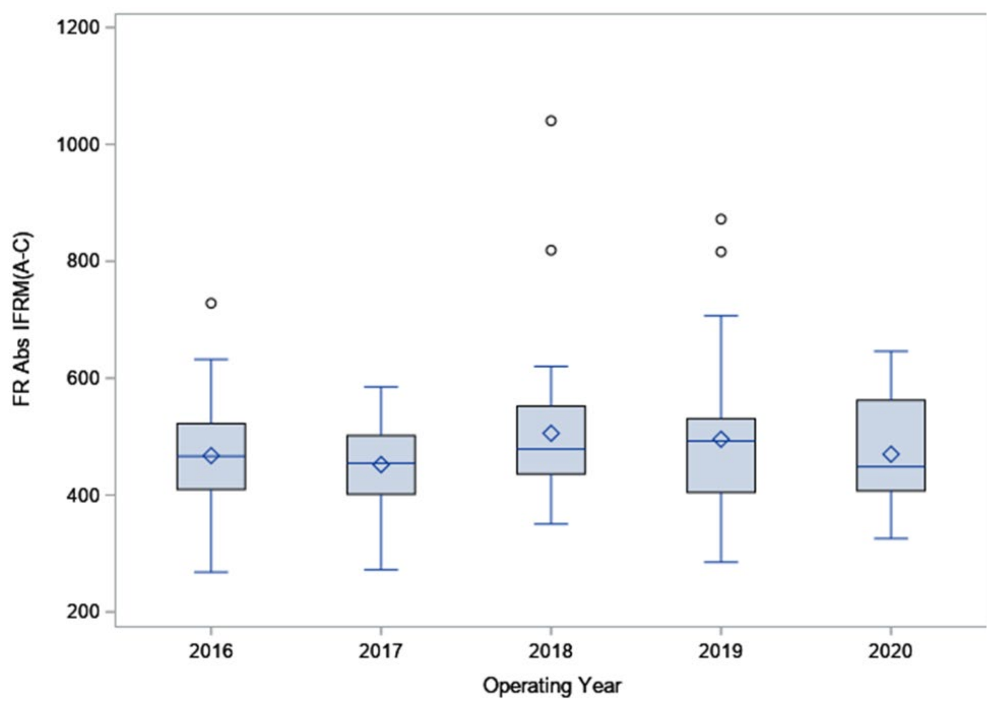

Figure A.4: Box Plots of Texas IFRM (A-C) Distribution by Operating Year 2016–2020

The 2020 Mean IFRM (A–C) was the third highest (and lowest) over the five years. Statistical tests found that the 2020 Mean IFRM (A–C) was statistically similar to the other four years (in **Figure A.5** the means are connected with the 2020 Mean by either a blue bar or a red bar).

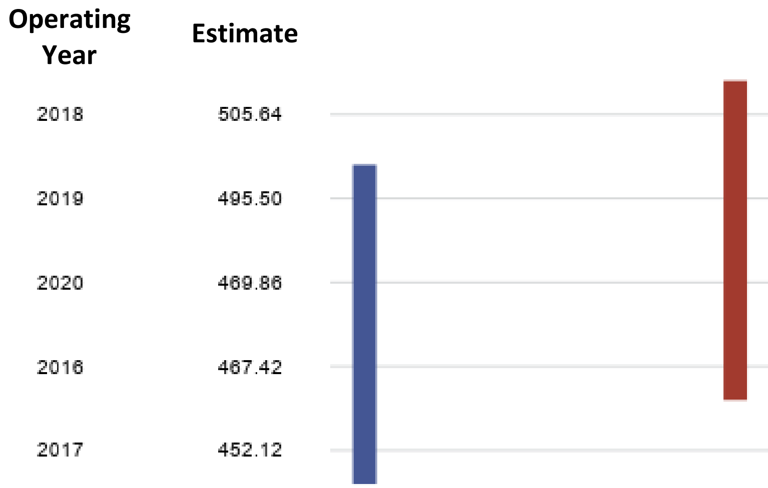

Figure A.5: Duncan Test for Texas IFRM (A–C) Mean for Operating Years 2016–2020

Texas IFRM (A-C): Time Trend

In the TI, a linear regression line (a trend line for the IFRM (A-C) mean) shown in **Figure A.6** has a positive slope which is not statistically significant (p-value=0.22). This result implies that it is likely that the positive slope of the trend line may have occurred simply by chance. It leads to the inference that from 2016–2020, the IFRM (A-C) in the TI has been neither decreasing nor increasing as measured by the mean.

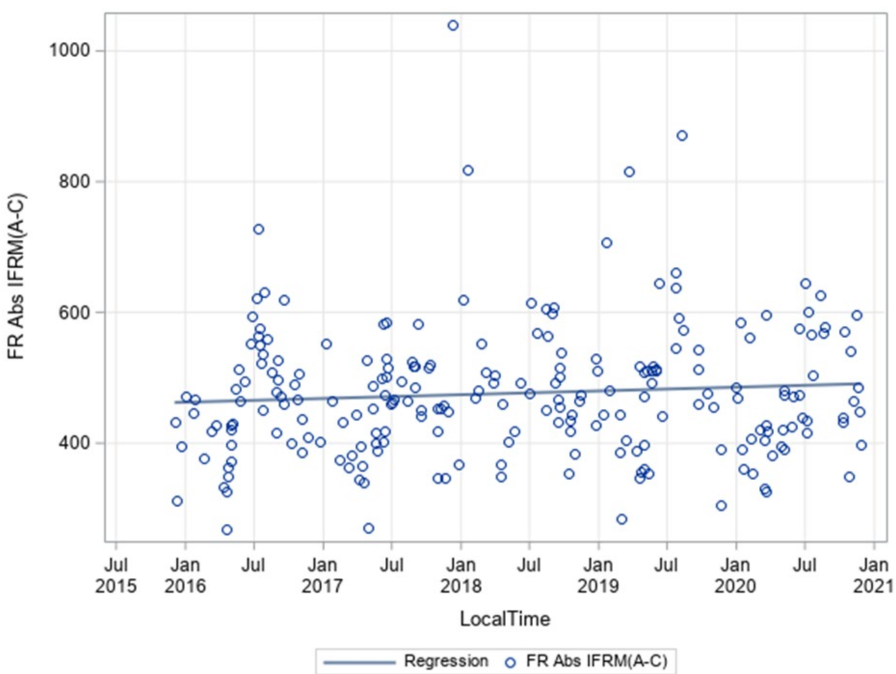

Figure A.6: Texas IFRM (A-C) Scatter Plot and Time Trend Line for Mean IFRM (A–C) in 2016–2020

Québec Interconnection

Québec IFRM (A–C): 5-Year Data and Annual Datasets

Table A.3: Descriptive Statistics for Québec Interconnection IFRM (A–C)						
Operating Year (OY)	Number of Events	Mean Frequency Response	Standard Deviation	Median	Minimum	Maximum
2016–2020	**311**	**133**	**30**	**127**	**54**	**292**
2016	47	138	30	140	76	242
2017	73	123	24	122	86	213
2018	82	134	27	127	86	267
2019	57	141	40	134	76	292
2020	52	129	28	127	54	197

Québec IFRM (A-C): Annual Distributions and Year-to-Year Changes

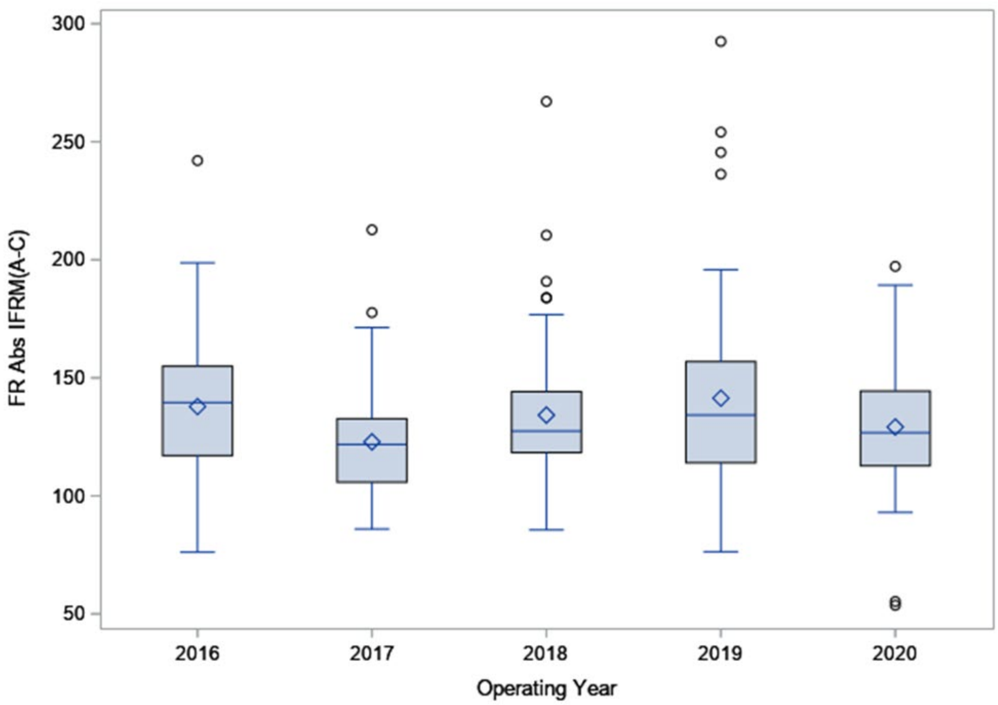

Figure A.7: Box Plots of Québec IFRM (A–C) Distribution by Operating Year 2016–2020

The 2020 Mean IFRM (A–C) was the second lowest over the five years. Statistical tests found that the 2020 Mean IFRM (A–C) was statistically similar to 2016, 2017, and 2018 and statistically significantly lower than the 2019 (the best year)—no bar connects the 2020 Mean and the 2019 Mean in **Figure A.8**.

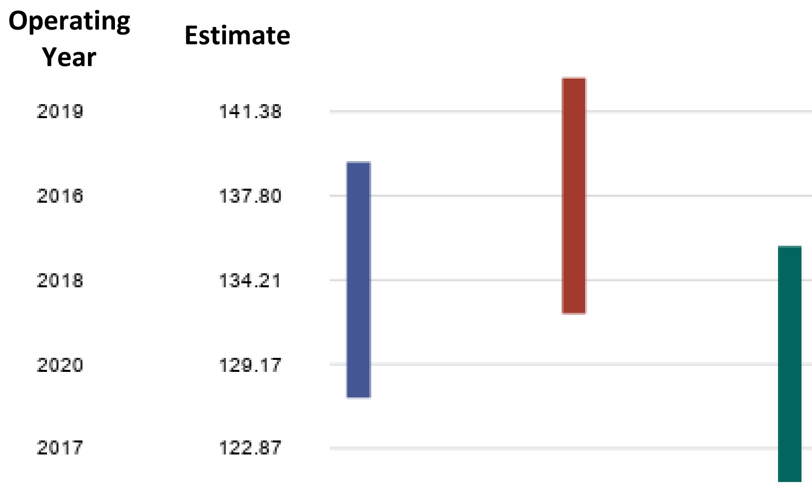

Figure A.8: Duncan Test for Québec IFRM (A–C) Mean for Operating Years 2016–2020

Québec IFRM (A-C): Time Trend

In the QI, a linear regression line (a trend line for the IFRM (A–C) mean) shown in **Figure A.9** has a negative slope which is not statistically significant (p-value=0.50). This result implies that it is likely that the negative slope of the trend line may have occurred simply by chance. It leads to the inference that from 2016–2020, the IFRM (A–C) in the QI has been neither decreasing nor increasing as measured by the mean.

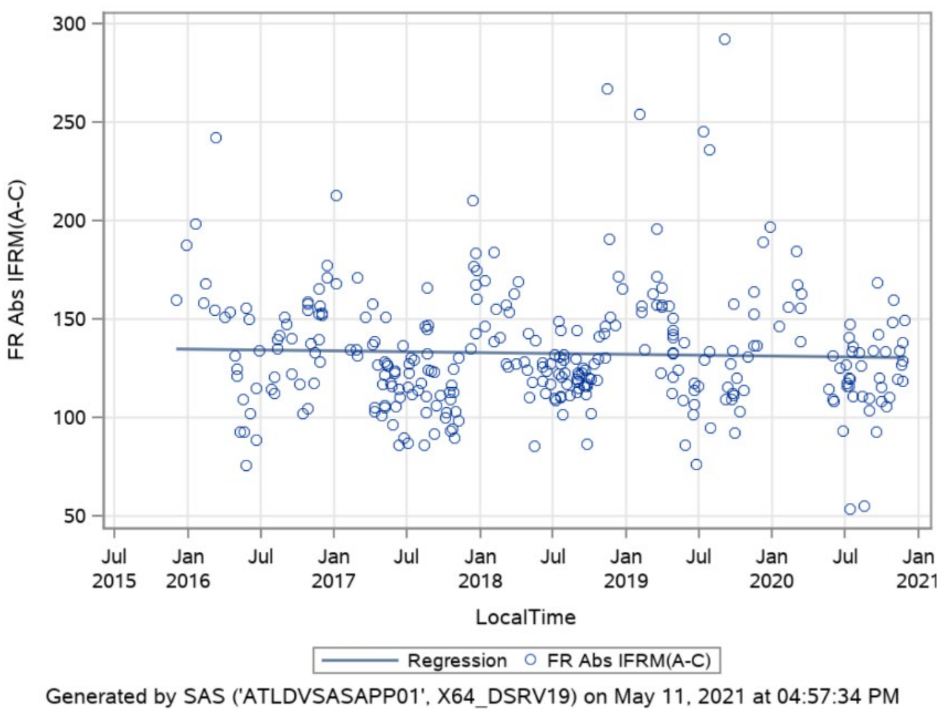

Figure A.9: Québec IFRM (A-C) Scatter Plot and Time Trend Line for Mean IFRM (A-C) 2016–2020

Western Interconnection

Western IFRM (A–C): 5-Year Data and Annual Datasets

Table A.4: Descriptive Statistics for Western Interconnection IFRM (A–C)						
Operating Year (OY)	Number of Events	Mean Frequency Response	Standard Deviation	Median	Minimum	Maximum
2016–2020	**200**	**867**	**228**	**841**	**373**	**1,737**
2016	47	827	177	804	525	1,375
2017	41	881	255	898	373	1,580
2018	43	840	180	847	419	1,179
2019	37	856	275	832	408	1,737
2020	32	955	245	978	381	1,649

Western IFRM (A–C): Annual Distributions and Year-to-Year Changes

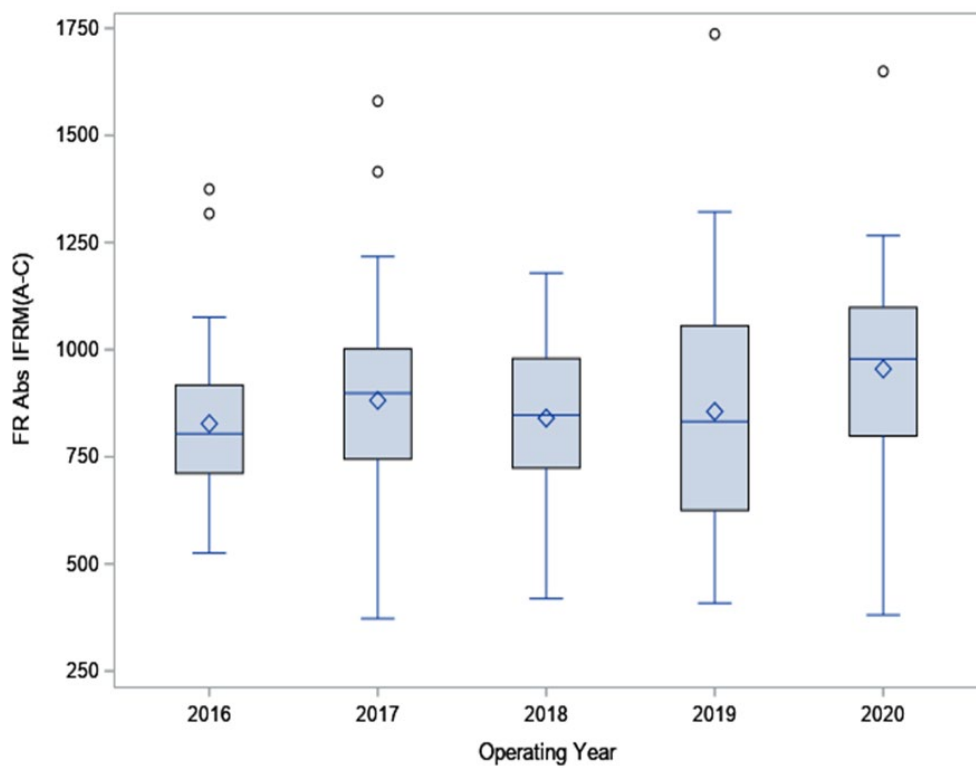

Figure A.10: Box Plots of Western IFRM (A–C) Distribution by Operating Year 2016–2020

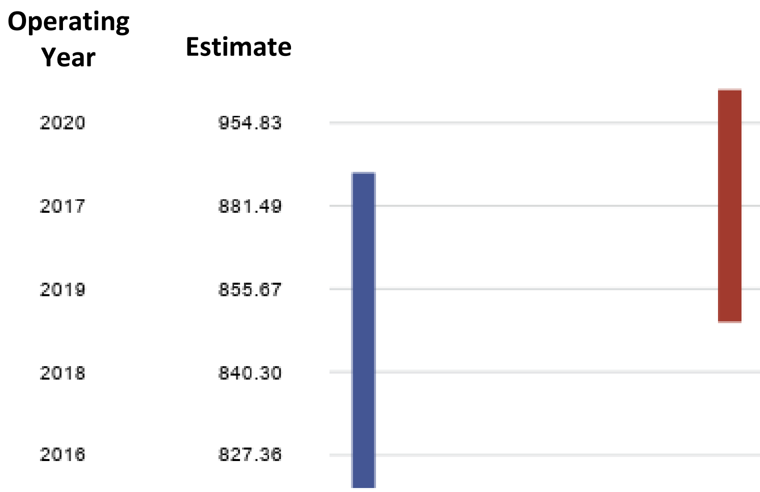

Figure A.11: Duncan Test for Western IFRM (A–C) Mean for Operating Years 2016–2020

The 2020 Mean and Median IFRM (A–C) were the highest over the five years. Statistical tests indicate that the 2020 mean was statistically significantly better than in 2016 and 2018 and statistically similar to 2017 and 2019.

Western IFRM (A-C): Time Trend

In the WI, a linear regression line (a trend line for the IFRM (A-C) mean) shown in **Figure A.12** has a positive slope which is statistically significant (p-value=0.04). This result implies that it is unlikely that the positive slope of the trend line may have occurred simply by chance. This leads to the inference that from 2016–2020, the IFRM (A–C) as measured by the mean has been increasing at the annual average rate of 21.2 MW/Hz*0.1.

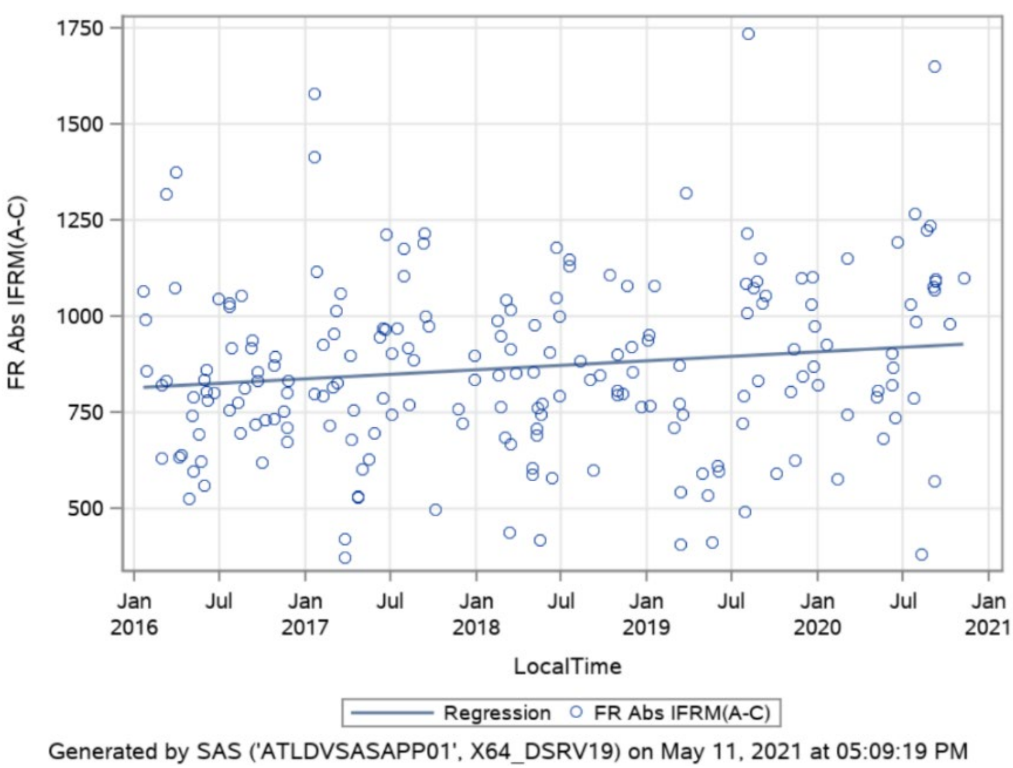

Figure A.12: Western IFRM (A–C) Scatter Plot and Time Trend Line for Mean IFRM (A–C) in 2016–2020