Priority-based
Control
Engineering

Directed Research to Validate Balance Resources and Demand Standard's Procedures and Define Frequency-related Limits

Final Integrated Report

Phases I and II

Prepared by

Priority-based Control Engineering (PCE)

For

Consortium for Electric Reliability Technology Solutions (CERTS)

in response to

NERC Directed Research Requirements

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Directed Research to Validate Balance Resources and Demand Standard's Procedures and Define Frequency-related Limits

Prepared by

Priority-based Control Engineering
6063 Frantz Road, Suite 205
Dublin, OH 43017-3370
(614) 799-0300

Principal Investigators

Nasser Jaleeli

Alex Podolsky

Brian J. Birch

Prepared for

Consortium for Electric Reliability Technology Solutions

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I. Abbreviations and Definitions

ACE – Area Control Error

AIES – Alberta Interconnected Electric System

BA – Balancing Authority

BAAL – BA ACE Limit

BRD SDT – Balance Resources and Demand Standard Drafting Team

CERTS – Consortium for Electric Reliability Technology Solutions

Contingency operation – Interconnection operation during a period of time that starts from occurrence of a load or generation contingency and ends when the frequency recovers from that event.

ECAR – East Central Area Reliability Council

ERCOT – Electric Reliability Council of Texas

FAL – Frequency Abnormal Limit

FPL – Florida Power and Light Company

FRCC – Florida Reliability Coordinating Council

FRL – Frequency Relay Limit

FTL – Frequency Trigger Limit

GADS – Generation Availability Data System

MAAC – Mid-Atlantic Area Council

MAIN – Mid-America Interconnected Network, Inc.

MAPP – Mid-Continent Area Power Pool

Method of Least Squares – A method of determining the line that best describes the relationship between expected and observed sets of data by minimizing the sums of the squares of deviation between observed and expected values.

NAESB – North American Energy Standards Board

NBP – New Brunswick Power

NERC – North American Electric Reliability Council

Non-contingency operation – Interconnection operation at any time the Interconnection is not in contingency operation. See *contingency operation* above.

NPCC – Northeast Power Coordinating Council

NWPP – Northwest Power Pool

P-Frequency-Response – Pre-reversal Frequency Response. As used in this report, this value is the ratio of the contingency size to the expected resulting maximum frequency deviation. Here, supply-side events are assumed to have a positive contingency size, while demand-side events have a negative contingency size. This maximum frequency deviation occurs at the point where the increase in the magnitude of frequency deviation is arrested by the action of primary response. This is also the point where the frequency trend reverses and frequency begins to move towards schedule.

PCE – Priority-based Control Engineering

RAS – Remedial Action Scheme

RC – Reliability Coordinator. Also known as Reliability Authority, or RA, in other contexts and in earlier drafts of this report.

SAR – Standard Authorization Request

SERC – Southeastern Electric Reliability Council

SPP – Southwest Power Pool, Inc.

SPS – Special Protection Scheme

Standard – Draft 4 of the proposed Balance Resources and Demand Standard. Also referred to as Standard 300 in earlier drafts of this report and some referenced documents.

T_{vb} – A limit on the number of consecutive minutes that a BA may allow its ACE to go above $BAAL_{high}$ or below $BAAL_{low}$ without violating the measures in the Standard. This limit is referred to as BAAL T_v in the Standard.

T_{vfh} – This parameter is referred to as FTL_{high}'s T_v in the Standard. The Standard defines it to be a limit on the number of consecutive minutes that the Interconnection frequency can be above FTL_{high} without exposing it to unacceptable risk.

T_{vfl} – This parameter is referred to as FTL_{low}'s T_v in the Standard. The Standard defines it to be a limit on the number of consecutive minutes that the Interconnection frequency can be below FTL_{low} without exposing it to unacceptable risk.

UFLS – Under-frequency load shedding

WECC – Western Electricity Coordinating Council

II. Executive Summary

1. Conclusions

The Standard defines a method of developing frequency and ACE limits, which are based on outage statistics and relay settings, and are intended to limit the rate of activation of frequency sensitive relays to a targeted bound. Under this Standard, RCs may incur violations when the frequency of their Interconnection continuously exceeds any of these frequency limits for longer than the associated time limits specified by the Standard. BAs may incur violations when their ACE exceeds a variable frequency-based ACE limit continuously for longer than T_{vb}, a time limit specified by the Standard.

The general concept of using unit outage statistics and a probabilistic approach to evaluate and limit the rate of load shedding due to the activation of UFLS relays is sound. The proposed method of setting FAL is conservative in regard to the risk of reaching relay limits. It is designed so that even if frequency is always at FAL during non-contingency operation, the risk of activating under- and over-frequency relays will remain within targeted bounds. Therefore, so long as frequency does not actually go beyond FAL during non-contingency operation, the risk of activating the relays should remain within targeted bounds.

In some cases this conservative procedure can result in low-side limits that are extremely tight or even above 60 Hz. Implementing the proposed process for WECC indicates that FTL_{low} can be anywhere from 59.856 Hz, when all generation trip events caused by RAS/SPS activation or loss of transmission facilities are ignored, to 60.075 Hz, when all such trips are considered.

Despite the conservative setting of FAL and some correlation between the measures in the Standard and bounding frequency to FAL, compliance with BAAL measures does not ensure that the risk of frequency reaching FRL will be limited to the targeted bound. BAAL measures require only that BA ACE not go beyond BAAL for a period longer than T_{vb}; the measures do not penalize a BA whose ACE often exceeds BAAL, but each time for less than T_{vb}, and the BA measures are blind to the magnitude of ACE once it exceeds BAAL. There are a number of potential situations in which BAs may cause frequency to move beyond FAL while remaining in compliance with these measures. It will depend on the extent to which BAs change their generation control practice to take advantage of the Standard. As a consequence, the rate of Interconnection's frequency reaching FRL can also exceed the targeted statistical bound. At the same time, limiting the number of consecutive minutes that BA ACE can exceed BAAL in some cases may impose a significant amount of control on BAs without noticeably decreasing the risk of frequency reaching FAL. PCE recommends that future research give priority to improving the design of the measures to properly bound the risk of reaching FRL before improving the rigorousness of the method of setting frequency limits.

If the industry chooses to approve the Standard as currently proposed, PCE recommends that NERC monitor frequency performance and, whenever changes in generation control practice cause frequency to exceed FAL at an unacceptable rate, tighten FTL_{high}, FTL_{low}, T_{vb}, T_{vfh}, and/or T_{vfl} to reduce this rate. The current procedure for setting T_{vfl} does not have a strong correlation with the objectives of the Standard; it allows an unrealistically long limit on the interval during which frequency can remain beyond FTL_{low}. T_{vfl} for all Interconnections have been provisionally set to the maximum limit of 30 minutes specified by the Standard.

The SAR for the Standard also requires maintaining Interconnection frequency performance within a targeted frequency profile. BRD SDT has chosen to limit RMS of frequency error one-minute averages to a targeted bound and has proposed CPM-1 to measure the contribution of BAs to helping the Interconnection meet this target. For the Interconnection one-minute average frequency error to meet the targeted RMS, ε_1, frequency cannot wander at levels much beyond 3 to 4 times of ε_1 away from scheduled frequency for more than a few hours per year. To help return frequency to its schedule when it is abnormally deviated and help meet the targeted frequency profile, it would be beneficial to limit FTL_{low} and FTL_{high} for each Interconnection to a setting in the range of 3 to 4 times of its ε_1 away from scheduled frequency, particularly FTL_{low} for WECC's and FTL_{high} for all Interconnections. BRD SDT's choice of FTL_{high} for the Eastern Interconnection during the Phase II of the Field Trial for the Standard is consistent with this proposal.

In addition to firm loads shed at FRL_{low}, some loads are shed at higher frequencies. For example, while FRL_{low} for WECC is set to 59.500 Hz, some non-firm loads are shed at frequencies as high as 59.900 Hz. Setting FTL_{low} somewhat higher than the frequency at which the first stage of non-firm loads is shed should help prevent a large increase in the rate of shedding such loads.

PCE examined the effectiveness and validity of the proposed BAAL measures. The proposed BAAL formulation ensures that if all BAs are within their BAAL at all times, the Interconnection frequency will not exceed FTL. Therefore, for frequency to exceed FTL, at least one BA must be outside its BAAL.

However, these features are not unique to the selected BAAL formulation; many different sets of formulations would have the same beneficial properties. The proposed BAAL formulation is based on an assumption that risk of reaching FRL is proportional to frequency deviation from schedule. Analysis presented in this report challenges this assumption. PCE proposes that, whether the Standard is approved by the industry or not, further research be conducted to develop measures that are more correlated to the risk they aim to limit.

BAAL measures may not be necessary for single-BA Interconnections. For example, in case of ERCOT, ensuring that frequency returns within FTL is equivalent to ensuring that the ERCOT's ACE returns to within its BAAL. Therefore, complying with the RC measures of the Standard is sufficient for ensuring that the BA remains compliant with the BA measures of the Standard.

Furthermore, preliminary analysis indicates that the proposed BAAL measures may result in a decreased number of violations as a result of aggregate reporting of ACE. This may mean more expected violations for smaller BAs for the same proportional amount of control and induced Interconnection risk as larger BAs. PCE recommends that this subject be further explored in future research.

2. Phase II Objectives and Deliverables

CERTS subcontract for Phase II specifies that PCE will perform the analysis and deliver the items listed in the left column of Table 1. The right column of that table summarizes the results. The results of Phase II work are combined with the last Draft of Phase I report released on January 6, 2005, to produce this integrated report.

See Appendix F for more detailed tables regarding the status of and suggested further research stemming from Directed Research objectives.

Table 1. Specific Analysis and Deliverables for Phase II of Directed Research.

Analysis and Deliverables for Phase II	Status
Description of data acquired for the project. Refinements to the method for calculating FAL and FTL proposed to BRD SDT; updated software of the method for calculating FAL and FTL reflecting any BRD SDT adopted refinements, if any, as well as the associated updated estimates of FRL_{low}, FAL_{low}, and FTL_{low} for the Eastern Interconnection reflecting any BRD SDT adopted refinements.	Data gathered from sources described in this report. Process and software refined to use historical recovery rate and estimate the limits. FRL_{low} = 59.820 Hz FAL_{low} = 59.908 Hz FTL_{low} = 59.950 Hz

Table 1. Specific Analysis and Deliverables for Phase II of Directed Research; cont'd.

Analysis and Deliverables for Phase II	**Status**
Estimates of FRL_{low}, FAL_{low}, and FTL_{low} for the WECC Interconnection.	FRL_{low} = 59.500 Hz Depending on the set of generation trip events caused by loss of transmission facilities or activation of protection schemes that is considered, the proposed process can give a wide range of values for FAL_{low} and FTL_{low} for WECC. When the probabilities associated with all events in the set are included, the proposed process gives (note that FTL_{low} is higher than 60 Hz): FAL_{low} = 59.943 Hz FTL_{low} = 60.075 Hz In the other extreme, if the probabilities associated with all events in the above defined set are ignored, the proposed process gives: FAL_{low} = 59.722 Hz FTL_{low} = 59.856 Hz It may be necessary to limit the FTL in WECC to a setting in the range of 3 to 4 times of its ε_1 in order to help one-minute average frequency error to meet the targeted RMS as required by the Standard. This constraint should also help prevent a large growth in the shedding rate of non-firm loads.
Estimates of FRL_{low}, FAL_{low}, and FTL_{low} for the ERCOT Interconnection.	FRL_{low} = 59.300 Hz FAL_{low} = 59.622 Hz FTL_{low} = 59.932 Hz
Report of estimates of frequency limits for the three Interconnections in a format similar to that of Table 3 in section VIII of the Phase I Report, and will revise Appendices A and B of the Phase I Report to reflect any BRD SDT adopted refinements, if any.	Summary of frequency limit calculations is provided in section VIII of this integrated report. Appendices A and B have been revised and Appendix D has been added to reflect BRD SDT-adopted refinements.

III. Background

1. Historical Objectives of Generation Control

Traditional objectives of ACE/frequency control have included reduce the incidence of unscheduled flows likely to induce congestion in transmission facilities, bounding inadvertent energy exchange among the control areas, and preventing/reducing time error. Another major objective has been to ensure that frequency remains away from levels that would cause under- or over-frequency relays to be activated. Extremely low frequency can lead to shedding firm load, while high frequency can cause wear and tear in generating equipment. Additionally, those entities that cause the Interconnection to operate at a lower frequency cause a reduction, due to load response, in other members' paying load.

2. Project Purpose

The purpose of this research is to validate that the following processes and their supporting concepts are technically sound and will be effective if implemented by the industry:

- Process for developing Frequency Limits.
- Process for developing BAALs.

The validation process requires using actual data to determine whether the limits can be developed as proposed, and then using actual data to show whether the limits work as intended for various sized BAs in each of the major Interconnections (Eastern, Western, ERCOT). The process for developing frequency limits and the process for developing BAALs are embedded in the Draft 4 of the Standard as BAL-011-1 and BAL-012-1, respectively [1].

The SAR for the Standard defines the objective of the Standard to be:

> *To maintain Interconnection scheduled frequency within a predefined frequency profile under all conditions (i.e. normal and abnormal), to prevent unwarranted load shedding and to prevent frequency-related cascading collapse of the interconnected grid.* [19]

It is understood that, in the above objective, the phrase "Interconnection scheduled frequency" means "Interconnection operating frequency".

The SAR states the following requirements for the Standard:

(a) This standard will maintain Interconnection frequency performance within a targeted frequency profile as demonstrated through control performance measures.

(b) This standard will require the use of a technically defensible mathematical method to enable each Interconnection to disburse control responsibility among its entities to achieve its targeted Interconnection frequency profile.

(c) This standard will require that the Reliability Authority have the authority to monitor system frequency and have the authority to direct actions (to control frequency) that include load shedding.

In this report, the phrase "technically defensible mathematical method" of disbursing responsibility, mentioned in (a) above, is understood to mean a method that can be mathematically shown to be probabilistically ensuring the expected level of reliability as defined by NERC while fairly distributing responsibility to Interconnection BAs of different sizes.

PCE has understood and made the following assumption in conducting the research in this report that:

- Other standards defined by NERC and NAESB will attend the other crucial characteristics and objectives of proper interconnected operation that have traditionally been addressed using ACE/frequency control. In particular, other standards will be responsible to limit the number of congestion events in transmission facilities due to flows associated with diversified large ACEs.

- CPM-1 will be implemented as described in the Standard with the current ε_1 targets remaining unchanged for all NERC Interconnections. This ensures that the one-minute average frequency profile of the Interconnections will remain within historically reliable bounds, subject to all BAs' compliance with the Standard.

With that in mind, PCE commends NERC's goal of developing a Balance Resources and Demand Standard in order to reduce the amount of unnecessary control, while maintaining reliability and security of the Interconnections, and fairly distributing control responsibility among Interconnection participants. The principal component of frequency control, generation control, has an impact on the order of many hundreds of millions of dollars on North American utilities and their customers, and that figure can be reduced with standards more closely tied to the objectives of interconnection reliability.

3. Scope of this Report

This report develops and provides the deliverables listed in column 1 of Table 1 along with updated deliverables from Phase I of this project. These deliverables have been deemed by CERTS and PCE to have the highest priority out of the tasks described in the complete Directed Research included in Appendix E. The report evaluates as many procedures in the Standard as possible, within the constraint of allocated resources. These procedures have been evaluated to determine whether implementing the Standard would limit the expected occurrence of activating the under- and over-frequency relays each to once per 10 years. The report also discusses the relationship of these procedures and realization of a targeted frequency profile. In addition, it analyzes the proposed processes for developing frequency limits and BAALs, evaluates the consistency and validity of these processes, and estimate the low-side frequency limits for the Eastern Interconnection, WECC, and ERCOT.

4. Scope of the Operation During Which the Rate of Load-Shedding Is to be Bounded

The once-per-10-years targeted risk of activating the under- and over-frequency relays specified in the Standard as acceptable excludes the activation of such relays occurring in islands separated from the bulk of an Interconnection. This exclusion applies irrespective of the cause of such separations, even if any of them is due to aggregate impact of mismatch between resources and demand in various BAs on some transmission facilities.

The above targeted risk also excludes the activation of such relays in an Interconnection during times of abnormal operation such as natural disasters impacting a significant portion of an Interconnection or disconnections of significant portions of an Interconnection.

IV. Validate the Concept of Using Probabilistic Acceptable Risk Limits, Based On Unwarranted Under Frequency Load Shedding and Unit Outages

1. Summary

The proposed method of frequency control requires the Standards Developer to develop frequency limits. These limits should ensure that: i) the expected rate of occurrence of load-shedding events due to negative frequency excursions does not exceed one in 10 years and ii) the same is true for the expected rate of occurrence of over-frequency generator relay trips due to positive frequency excursions. PCE finds sound the concept of limiting unwarranted under-frequency load shedding as an important factor in establishing frequency limits and using the probability of generating unit outages (along with multi-unit plant outages and HVDC line or converter trips) as a factor in defining these limits. PCE has also found that the probabilistically calculated frequency limits used to define requirements in the Standard are likely to have a noticeable effect on the risk of load-shedding occurrences.

However, given the generation control performance measures in the Standard, PCE believes that too many parameters, such as future generation control practice, can affect the risk of frequency reaching FRL_{low} associated with any particular value of FTL_{low}. Therefore, it is impossible to estimate with any practical accuracy the rate of load-shedding events associated with any value of FTL_{low}, including the one derived using the proposed process. The fact that a value of FTL_{low} will be derived for the purposes of this report should not imply that the measures in the Standard make it possible to guarantee that the risk of reaching FRL_{low} associated with this value of FTL_{low} will be acceptably bounded.

PCE suggests that further research be performed to study the impact on the risk of the measures in the Standard failing, due to potential real-time errors in calculated ACE and measured frequency, to prevent frequency from reaching FRL more than once in 10 years.

PCE also notes that it may be beneficial, and potentially vital, to the proper operation of the NERC Interconnections to consider other factors in setting the frequency limits proposed in the Standard. One of these factors is the goal of maintaining the targeted frequency profile, as required by the SAR. Another is preventing substantial growth in the rate of activating frequency-based interruptible-load shedding relays.

2. Frequency Control under the Standard

BRD SDT proposes to create measures based on the frequency limits to prevent load shedding as follows. Measures are expected to impact generation control practice in a way that bounds the tails of the probability distribution of frequency error. The goal is to ensure that frequency does not reach and stay below FRL_{low} for a period of time sufficient to activate load-shedding relays[1] more than once every 10 years. The Standard would achieve this goal through control measures,

[1] With the current relay setting choices this period is 10 cycles or about 0.167 s for the Eastern Interconnection.

which are designed to prevent frequency from reaching FAL_{low}. One of those measures will be setting FTL_{low} to a value that allows sufficient time for BAs and RCs to take action before reaching FAL_{low}.

PCE's understanding of the method of setting frequency limits outlined in the Standard is as follows. FAL_{low} should be set at the lowest value where the frequency will not be expected to reach the associated FRL_{low} more than once in 10 years as a result of a generation-loss event, even if frequency is at this particular FAL_{low} at all times in this 10-year period during non-contingency operation[1]. As a result, preventing frequency from going beyond FAL_{low} during non-contingency operation significantly increases our confidence that frequency will not reach FRL_{low} more often than once per 10 years even during contingency operation.

In this report, PCE has described a method of estimating the maximum frequency change resulting from contingencies that is expected to happen at least once every 10 years. An estimate of the magnitude of that frequency change for the NERC Interconnections is performed in section VIII.

The Standard intends to prevent frequency from going beyond FAL_{low} through the following measures:

- Penalizing BAs that remain beyond their BAAL limits for a period longer than T_{vb}.
- When frequency is beyond FTL_{low}, encouraging coordination between RCs and BAs to get frequency above FTL_{low} within the specified time limit (T_{vfl}).
- Penalizing RCs when their Interconnection frequency is beyond FAL_{low} for any amount of time, whether the RC had taken action or not.

The expected success of these measures in preventing frequency from going beyond FAL_{low} is discussed in other sections of this report.

3. Associating the Risk of Reaching FRL with a Setting of FTL

PCE understands that the proposed process for calculating FTL_{low} and FTL_{high} sets these limits by:

a) finding the highest contingency not considered for setting the corresponding FAL (considering generation losses to have a negative value and load losses to have a positive value),

b) dividing it by the estimated Interconnection frequency response (the result of this step has a positive value for generation losses and a negative value for load losses),

c) adding the result to the appropriate FAL.

In case of FTL_{low} for the Eastern Interconnection, the highest combined contingency not considered for setting FAL_{low} would be a trip of a power plant with expected output of around 2,500 MW. The FTL_{low} resultant from considering this to be the next highest contingency would be above 60 Hz.

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[1] See section I for definitions of *contingency* and *non-contingency operation*.

Moreover, simply adding one more contingency to calculate FTL does not have a sound theoretical basis. The calculation of FAL_{low} should exhaustively take into account the probability of all possible combinations of contingencies. It is highly unlikely that generation outages of a combined magnitude necessary to move the frequency all the way from FTL_{low} to FRL_{low} will occur within a short time of each other. Using the method described in section VII, PCE estimates that, excluding natural disasters and other events which preclude assumption of independence of events mentioned above, the Eastern Interconnection is not expected to experience an immediate loss of 4,000 MW due to generation contingencies more than once every 500 years.

The above conclusion is only true when trips of units and power plants are independent of each other (e. g. the trips are not caused by events that lead to the separation of a large section of an Interconnection). PCE understands that the independence assumption does not hold in case of coordinated generation shedding schemes, particularly those prevalent in WECC to maintain Interconnection integrity. Independence of generation contingencies also does not hold in case of a loss of generation due to the transmission-related separation of that generation from the bulk of the Interconnection.

To estimate FTL for the Eastern Interconnection, PCE used the contingency equivalent to a trip of the largest single unit. This approach is in line with the definition of contingency used in some existing NERC standards and has been approved by BRD SDT. However, PCE does not see that the use of any single contingency or combination of contingencies to calculate FTL based on FAL has a sound technical basis.

PCE is not proposing an improvement to this method of calculating FTL that would ensure a targeted rate of reaching FRL. Nor does PCE believe that, given the generation control measures based on FTL in the Standard, a reliable method is available for evaluating the risk of reaching FRL associated with a particular value of FTL.

However, if the non-contingency operation frequency distribution resulting from implementing the measures in the Standard turns out to be less risky than the one assumed by the proposed process for setting FAL, then the risk of reaching FRL under the Standard will be within targeted probabilistic bounds. This would be true if frequency is never beyond FAL during non-contingency operation. Alternatively, the control performance measures based on FTL that are proposed in the Standard could be modified to make possible a more reliable calculation of risk stemming from their implementation. This should be a subject for further discussion and analysis.

4. ACE and Frequency Errors

It is important to remember that real-time control to the Standard would be working with non-audited values of ACE and frequency and, therefore, the Standard should take into account the impact of possible errors in data entry, telemetry, or calculation. PCE has heard anecdotal evidence of more than a few cases in which control areas operated with an erroneous ACE for extended periods of time. The expected error in the Interconnection ACE times frequency error for a given time interval can be estimated using available historical CPS1 scores and historical data from a reliable frequency source, assuming that the effect of errors in CPS1 calculations is negligible.

Future research could undertake a study of the impact of errors in real-time ACE and frequency measurements on i) the risk of frequency reaching FRL and ii) the risk of failing to maintain the targeted frequency profile, even while all BAs and RCs are complying with the proposed requirements as indicated by the real-time measurements of ACE and frequency error.

5. Alternatives to Contingency-based Operational Deadbands for Limiting Risk

The Standard specifies that the frequency deadband in which an Interconnection may operate reliably is between the following frequency levels:

(a) The magnitude of a potential frequency drop resulting from a one-in-10-years combination of generation contingencies plus that resulting from another large unit trip added to the highest UFLS setting.

(b) The magnitude of a potential frequency rise resulting from a one-in-10-year combination of load loss plus that resulting from another large load loss subtracted from the lowest unit trip relay setting.

This approach is generally very conservative with regard to the triggering of frequency-activated relays. If frequency could, in fact, be maintained within the above deadband during non-contingency operation, the rate of activating such relays would be far smaller than once in ten years. Moreover, this process can be conservative to the point where, if generation or load trips due to other causes, such as loss of transmission or right-of-way, are taken into account, the low-side limits computed using this process become very close to 60 Hz and, as shown in section VIII, potentially above 60 Hz. In addition to transmission failures, in WECC, this is a result of various RAS mechanisms, which cause recurring generation losses far larger than the expected generation losses due to independent plant trips. In ERCOT, historical frequency data indicates that it might be impossible to ensure a one-in-10-year relay trigger rate due to all causes. A combination of contingencies caused a 720 mHz frequency drop and, consequently, a load-shed event in 2003. If we consider the possibility that this event may happen more than once in 10 years, the low-side frequency limits would become much higher than 60 Hz.

As discussed in the report for Phase I of this project, this approach is mainly very conservative because frequency will not be at FAL or even at FTL the entire 10 years. Nevertheless, PCE believes that it is necessary to be very conservative in selecting these frequency limits, in part because the proposed BA measures, which are based on them, are not sufficient to ensure frequency remaining limited to FAL even if all BAs are compliant.

An alternative measure of risk may be obtained by estimating the frequency distribution that is expected to be realized under the proposed measures, such as CPM-1, and then using this distribution together with available statistics on loss of various sizes of generating units and plants to evaluate the expected probability of reaching FRL. FTL and the associated BAALs should then be set so as to limit that risk by mitigating large frequency excursions.

In addition, as meeting a targeted frequency profile is defined as one of the objectives of the Standard, FTL should be limited so that action is taken quickly when large frequency deviations occur. The Interconnection should disallow large frequency deviations to persist for several minutes as they can threaten to make the one-year RMS of one-minute frequency error averages larger than ε_1 of the Interconnection. An approach of setting frequency limits with these considerations in mind is treated in more detail in section XI.2.

Finally, since avoiding all unwarranted frequency-related load shedding is defined as one of the objectives of this Standard in the SAR, it is important to prevent an increase in the rate of shedding frequency-activated non-firm loads, as well as the firm loads. Setting FTL_{low} somewhat higher than the highest setting of such automatic relays should help in accomplishing this objective.

V. Validate the Concept of Using Interconnection Frequency Response to Estimate Response to Generation/Load Mismatches

1. Summary

The Standard specifies that a frequency response value based on an average of the prior three years' data should be used to calculate the Minimum Safe Frequency Band. PCE has found that in order to properly estimate the Minimum Safe Frequency Band a measure of frequency response that reflects the estimated maximum frequency drop following a generation contingency of a given size can be used. Therefore, for the purposes of this report, a measure of frequency response, termed P-Frequency-Response (defined in section I and explained in section V.2 below), will be used. PCE believes that it is technically feasible and defensible to use estimated Interconnection P-Frequency-Response based on past frequency performance during generation and load contingencies.

The process could also be made more accurate and more cautiously conservative by taking into account the fact that risk is increased as a result of the variability of P-Frequency-Response.

2. P-Frequency-Response

In most cases, the full primary response of the Interconnection will not be realized before load-shedding relays activate. The peak frequency deviation better represents the impact of the contingency on the risk of tripping UFLS relays, since the quickest-opening relevant relays in the NERC Interconnections are set to open in 0.2 seconds or less. The net frequency deviation resulting from a contingency after the realization of the full frequency response (labeled "point B" in NERC frequency response survey guidelines [16]) will often be much smaller than the peak deviation in the same event (labeled "point C" in [16]).

To more accurately determine the impact of a generation-loss contingency on the risk of triggering relays requires a measure of frequency response that predicts the expected maximum frequency deviation resulting from a contingency of a given size. PCE has calculated such a measure and termed it *Pre-reversal Frequency Response* or *P-Frequency-Response*. As used in this report, P-Frequency-Response is the ratio of the contingency size in MW to the expected resulting maximum frequency deviation in 0.1 Hz. This maximum frequency deviation occurs at the point in time where the increase in frequency deviation is arrested by the action of primary response. This is also the point when the direction of frequency change reverses and frequency begins to move towards schedule.

P-Frequency-Response should be measured at the time of the absolute maximum frequency deviation. However, since the frequency data used to find the maximum frequency deviation is sampled at intervals of 2-6 seconds, the estimate of P-Frequency-Response calculated using the maximum frequency deviation in this data will have a higher magnitude than the actual value. Still, since the methods of setting the frequency limits are very conservative, for the purposes of the calculations in this report, we consider this to be a sufficiently accurate estimate.

Interconnection P-Frequency-Response can be estimated more accurately by studying sudden frequency change events using frequency data collected with a resolution of about 0.1 seconds. PCE is aware that some data with that resolution may be available for this type of analysis and recommends that this be performed in future phases of this research. Alternatively, data sampled at longer intervals can be interpolated to estimate a more accurate P-Frequency-Response.

3. Eastern Interconnection Response to Negative Frequency Events

PCE obtained Eastern Interconnection frequency event data from Elmer Bourque of NBP. PCE verified that the events recorded by NBP frequency measurements had a very good correlation with the generation trip data obtained from GADS. Sufficient data was available for 79 generation loss events occurring between 9/1/2001 and 8/31/04. NBP data included the approximate generation magnitude tripped for all but a few of these events. For those excepted few events, PCE used the average generation of the unit or plant during its service in that year as provided by GADS data. Having gone through this process, PCE recommends that, in order to increase the usefulness of the GADS database even more for Interconnection reliability research, GADS request and store data regarding the actual power loss due to immediate forced outages. Figure 1 shows one of the larger contingencies considered in this analysis.

A scatter plot of the frequency drop vs. the power loss for each of the above 79 events is shown in Figure 2. PCE then found the best-fit line for these points with the power loss as the independent variable using the Method of Least Squares. The slope of that best-fit line was used to determine the P-Frequency-Response of the Eastern Interconnection.

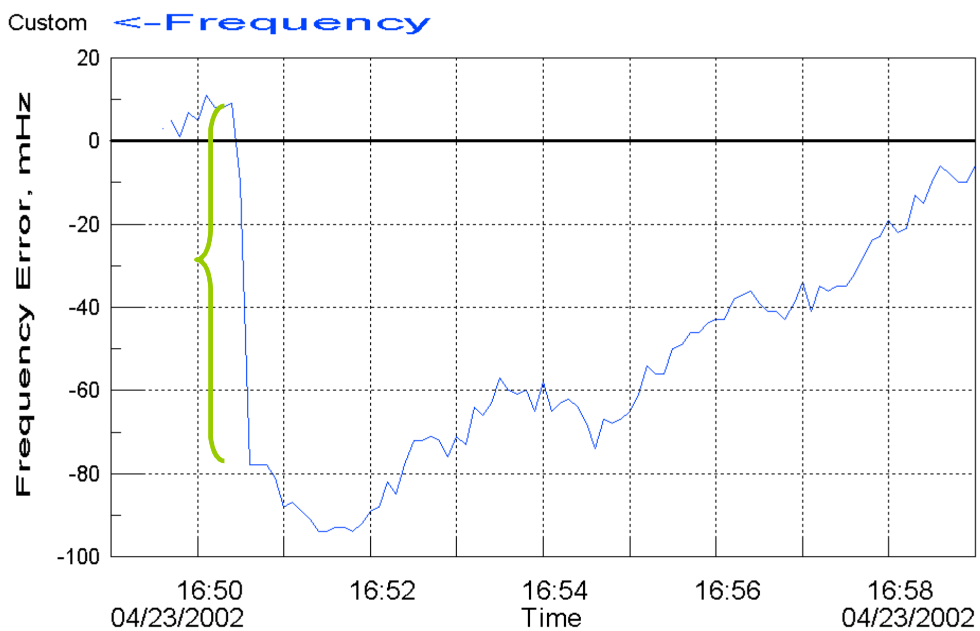

Figure 1. Eastern Interconnection frequency response to a large event. The bracket indicates the magnitude of the frequency drop considered for the estimate of P-Frequency-Response.

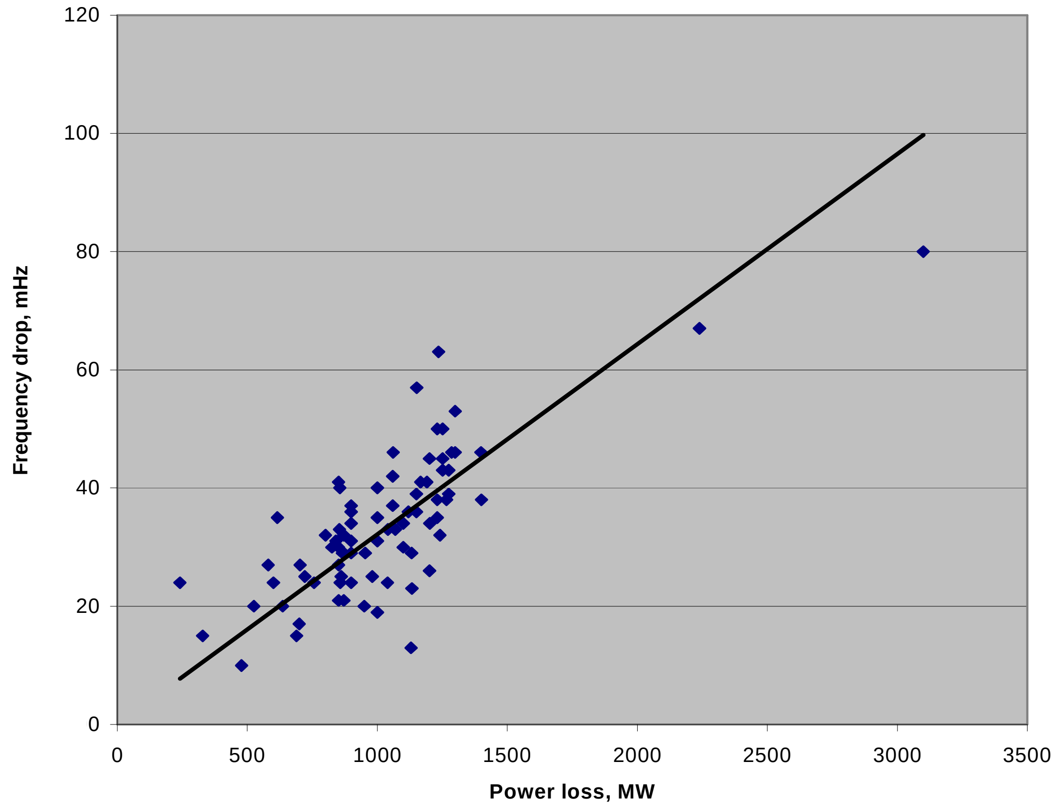

Figure 2. Scatter plot of the P-Frequency-Response to events recorded in the Eastern Interconnection.

Using the above method, the P-Frequency-Response to supply-side contingencies for the Eastern Interconnection was found to be -3,109 MW/0.1 Hz.

4. WECC Interconnection Response to Negative Frequency Events

PCE obtained data regarding generation contingencies in WECC from Don Badley of NWPP. This data includes the time and generation loss for 63 events from 2002 to 2004 where at least 800 MW was lost. PCE also obtained frequency data for the same time period from Yuri Makarov of California ISO and 2004 frequency data from Bart McManus of BPA. These three sources were used to validate each other. PCE then estimated the maximum frequency drop observed for each of the known events. Figure 3 shows one of the larger contingencies considered in this analysis.

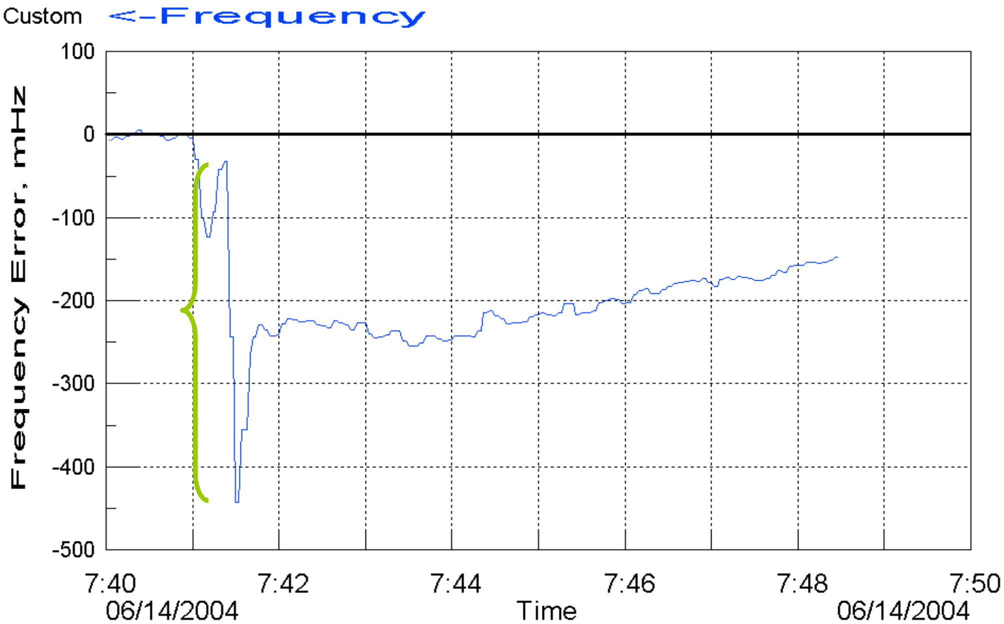

Figure 3. WECC frequency response to a large event. The bracket indicates the magnitude of the frequency drop considered for the estimate of P-Frequency-Response.

A scatter plot of the frequency drop vs. the power loss for each of these events is shown in Figure 4. PCE then found the best-fit line for these points with the power loss as the independent variable using the Method of Least Squares. The slope of that best-fit line was used to determine the P-Frequency-Response of WECC.

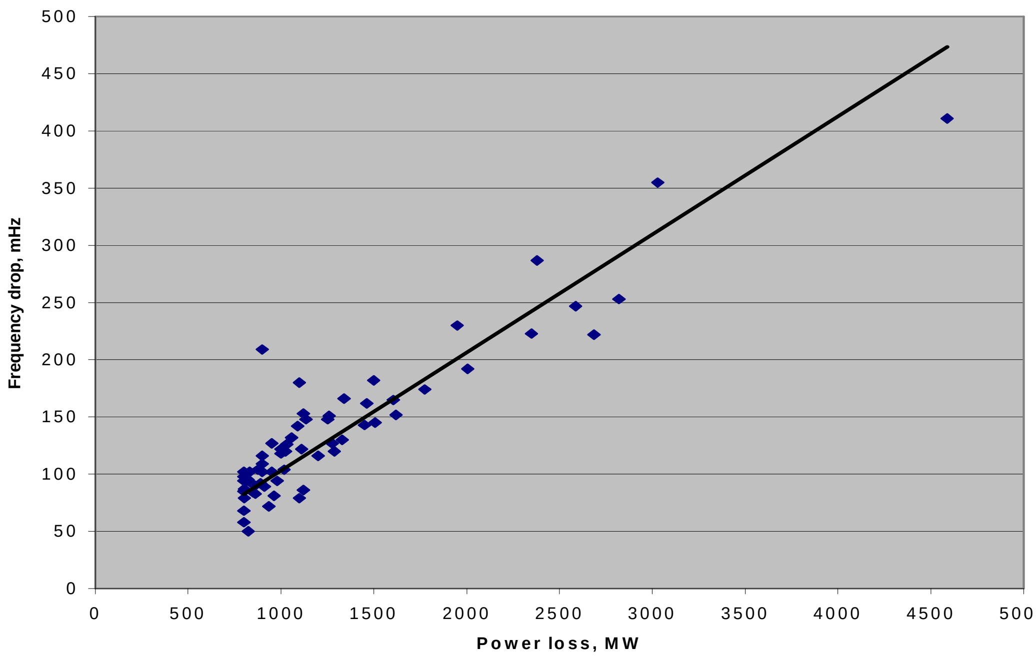

Figure 4. Scatter plot of the P-Frequency-Response to events recorded in WECC.

Using the above method, the P-Frequency-Response to supply-side contingencies for the WECC Interconnection was found to be -969 MW/0.1 Hz.

5. ERCOT Interconnection Response to Negative Frequency Events

PCE obtained data regarding generation contingencies in ERCOT from Mark Henry and Robert Staples of ERCOT. This data includes the time, generation loss, and frequency drop for 117 events from 2002 to 2004. ERCOT also provided 2-second frequency data for the same time period. The frequency data was used to validate the maximum frequency drop indicated in the contingency data. Figure 5 shows one of the larger contingencies considered in this analysis.

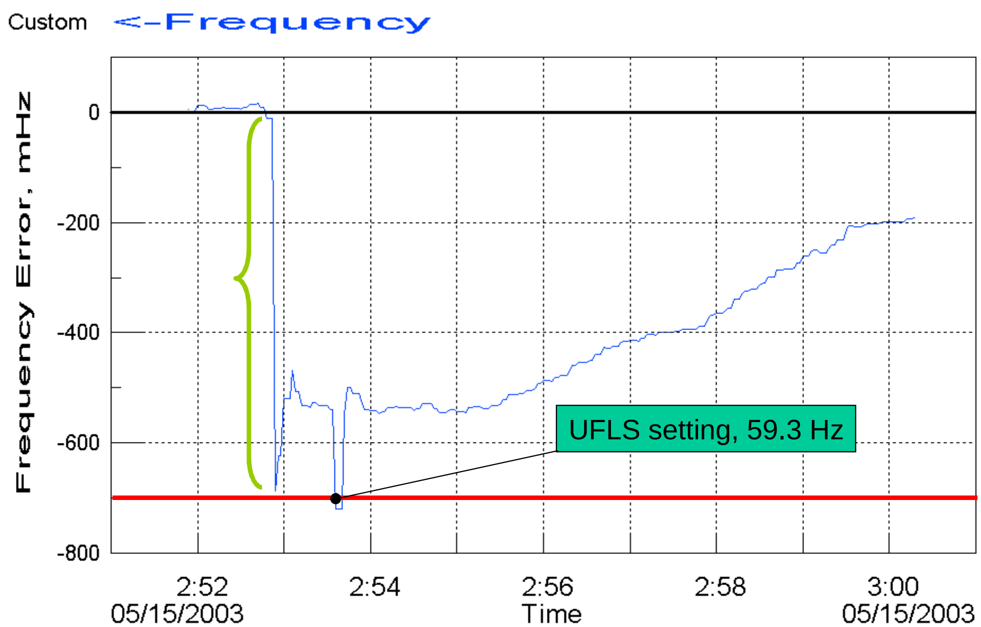

Figure 5. ERCOT frequency response to a large event. The bracket indicates the magnitude of the frequency drop considered for the estimate of P-Frequency-Response. The second event, occurring between 2:53 and 2:54, is not considered for calculation of P-Frequency-Response as frequency deviation resulting from it is influenced by UFLS shedding a large magnitude of load.

A scatter plot of the frequency drop vs. the power loss for each of these events is shown in Figure 6. PCE then found the best-fit line for these points with the power loss as the independent variable using the Method of Least Squares. The slope of that best-fit line was used to determine the P-Frequency-Response of ERCOT.

Using the above method, the P-Frequency-Response to supply-side contingencies for the ERCOT Interconnection was found to be -419 MW/0.1 Hz.

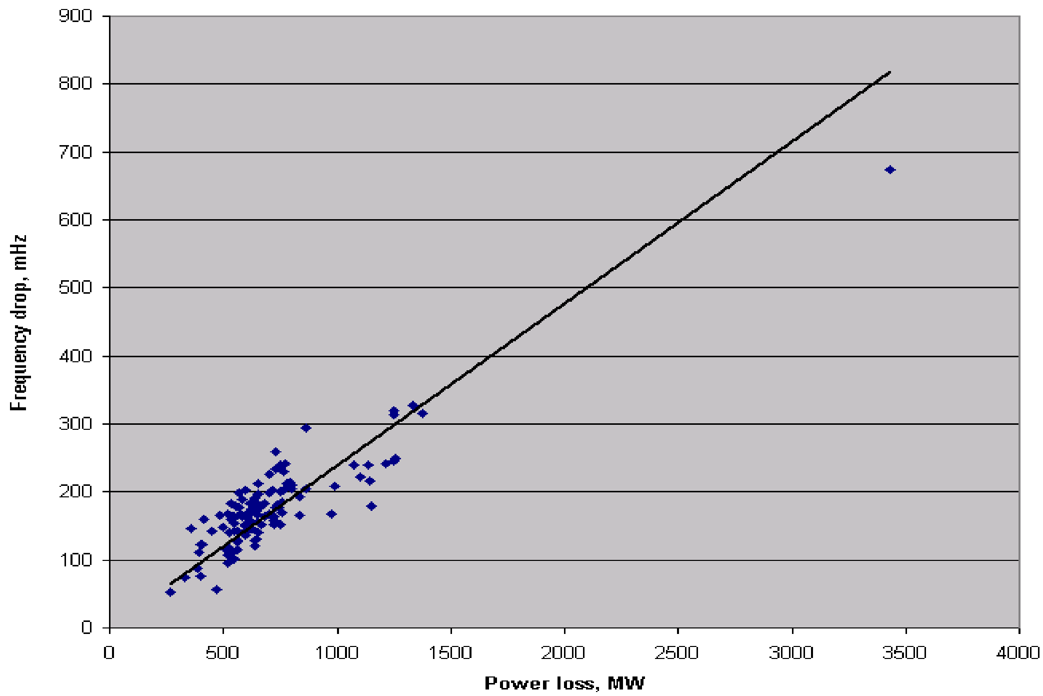

Figure 6. Scatter plot of the P-Frequency-Response to events recorded in ERCOT.

6. Consideration of Time Delay in Activation of UFLS Relays

Data provided to PCE by Don McInnis of FPL indicates that the load-shed relays located in FRCC, which PCE used to set FRL for the Eastern Interconnection in this report, will open within 10 cycles, or less than 0.2 seconds, of the moment at which frequency reaches FRL_{low}. As a consequence, a portion of primary response to the last contingency in a sequence of generation trips is highly unlikely to be realized in time to protect the load from being disconnected from the Interconnection.

In order to take this into account in estimating the Minimum Safe Frequency Band, the process should be changed to calculate the potential frequency change from each contingency directly, instead of computing the overall power change and dividing that by the single value of frequency response. This can be done as follows:

- When estimating whether a given single contingency would satisfy the proposed Minimum Safe Frequency Band, the frequency change would be calculated by dividing the power change by the P-Frequency-Response.
- When estimating whether a given combination of contingencies, separated in time, would satisfy the proposed Minimum Safe Frequency Band, the frequency change of the last contingency would be calculated by dividing the power change by the P-Frequency-Response. The frequency change due to prior contingencies can be calculated as follows: i) finding the time interval t_{aft} between that contingency and the final contingency in the combination, ii) for each historical event finding the expected ratio of the magnitude of

the generation loss to the frequency deviation t_{aft} seconds following the event, and iii) dividing the magnitude of the prior contingency by that ratio. When t_{aft} becomes approximately 6-8 seconds, that ratio becomes equal to the full primary frequency response. The frequency change due to contingencies occurring more than 30-60 seconds prior to the last contingency should also take into account the secondary response of the Interconnection. A basic method of modeling secondary response is described in Appendix D of this report.

7. Impact of Variations in Operating Conditions

Currently, the Standard does not take the impact of variations of P-Frequency-Response into account. The risk of reaching FRL increases as a result of the variations of P-Frequency-Response with season, time of day, activation of non-firm load-shed relays, and other factors. As suggested by Raymond Vice (Chairman, BRD SDT) of Southern Company, the process may also be improved by taking into account the fact that, following multiple generation contingencies over a period of time, frequency relays may act much earlier than anticipated because the bulk of the primary response on the system is utilized during the initial contingencies and is not available for frequency support during later contingencies [4]. The proposed process for setting frequency limits uses the approximation that P-Frequency-Response of the Interconnection is constant. As directed in [3], future research can expand on this analysis to determine how the variations in P-Frequency-Response impact the Interconnection risk of reaching FRL.

It is possible to account for the variations in P-Frequency-Response. In order to do so, the process of developing limits would have to be modified to estimate the Minimum Safe Frequency Deadband from contingency and P-Frequency-Response data directly, as proposed in section V.6. Doing so would allow the Standard Developer to account for the probability that generation contingencies of any given size could result in a larger or smaller than expected frequency drop.

In general, the process would find a probability distribution of frequency deviation associated with each level of power loss magnitude due to a single contingency. Using this distribution and the expected number of events of each magnitude over a targeted interval it would construct a distribution of frequency deviation for all events that may occur in a targeted interval. This distribution provides the probability of a given frequency drop due to a single contingency. This distribution can then be provided as an input to a modified version of the method developed by PCE. This method, which estimates the occurrence rate of various frequency drops due to combinations of contingencies, is introduced in section VII and described in more detail in Appendix B.

VI. Validate the Concept of Using Frequency-related Relay Settings to Establish Interconnection-wide Limits

1. Summary

PCE obtained information from all NERC Regions regarding the settings of UFLS relays that exist as part of Region- or Interconnection-wide protection schemes. As directed by the Standard, PCE used only the settings of those UFLS relays that disconnect firm load from the Interconnection.

PCE has found that the highest UFLS settings tend to be associated with RAS or SPS, designed to protect an area in case of islanding. UFLS relays installed to protect the bulk of the Interconnection in case of a severe imbalance between interconnection-wide resources and demand tend to have much lower settings.

Further research is necessary to accurately establish FRL_{high}.

2. Examining the Use of Frequency-related Relay Settings for Establishing Interconnection-wide Limits

The proposed process for developing frequency limits is based entirely around limiting the rate at which certain frequencies are reached. These bounding frequencies are defined by the settings of UFLS, as well as over-frequency and turbine-overspeed, relays.

PCE has found that the relevant low-frequency settings are well defined in all NERC regions. PCE's research has shown that every NERC region has approved a threshold beyond which a significant amount of firm load should be shed. This automatic load shedding acts as a last line of defense in case of a severe mismatch between resources and demand, and attempts to quickly arrest a runaway frequency. However, every load-shedding event is understood to have a significant cost defined mainly by its impact on the customers left temporarily without power. It is thus important to prevent cases where inadequate planning or improper operation by some participants leads to an imbalance between resources and demand that may result in load shedding. In order to reduce the occurrences of such widespread load shedding, it is reasonable to develop Interconnection-wide frequency limits in a way that bounds the likelihood of tripping these UFLS relays to a targeted value.

On the high frequency side, the process of selecting the relevant settings is more ambiguous. Most large units are designed to operate for a considerable amount of time at frequencies noticeably higher than 60 Hz. Research would be necessary to discover the amount of damage or wear and tear incurred by load components at various frequencies. At the same time, a positive runaway frequency in an intact Interconnection is believed to be extremely unlikely. PCE recommends that BRD SDT examine further the priority of various frequency-related reliability objectives when frequency is higher than 60 Hz, giving consideration to the objective of frequency meeting a targeted profile as required by the SAR for the Standard and discussed in the following paragraphs of this subsection.

PCE also recommends that the rate of shedding various frequency-activated interruptible loads be considered for assessing the reliability of operation. PCE is aware that there are loads shed at frequencies as high as 59.900 Hz in WECC. While it is not justifiable to set FRL_{low} to this value, it is clear that operation during which significant load is shed should not be considered normal operation and its occurrences should be kept within acceptable limit. It may be reasonable to set FTL_{low} somewhat higher than the setting of any frequency-activated load-shedding relays to provide an opportunity to alleviate the imbalance between resources and demand, and try to prevent trip of such loads.

Load-shedding and over-frequency relays should not be the only considerations in determining Interconnection risk stemming from the imbalance between resources and demand. In some cases, they may not be the limiting considerations. The SAR for the Standard requires that the Interconnection remain within a targeted frequency profile. While CPM-1 tracks the average of the products of one-minute average of ACE of every BA and that of frequency error over one-year periods, a real-time measure should address this issue as well since maintaining the desired frequency profile remains a high-priority objective. Since remaining at frequencies several times ε_1 away from schedule for even a short interval makes it unlikely that the associated Interconnection's profile will remain within the targeted bounds, the frequency limits set in this Standard need to enable RCs and BAs to avoid allowing frequency to reach these values. The limits for frequency should be set so that the Interconnection cannot remain beyond them for periods totaling more than a very small fraction of the time without violating the targeted frequency profile.

3. Under-frequency Relay Settings for the Eastern Interconnection

PCE researched and received information for NERC Regions in the Eastern Interconnection. The most up-to-date information available to PCE is listed in Table 2 below.

Table 2. Highest approved firm load UFLS settings of Eastern Interconnection Regions.

NERC Region	Highest UFLS (firm load) setting
ECAR	59.500 Hz [6]
FRCC	59.820 Hz
MAAC	59.300 Hz [7]
MAIN	59.300 Hz [8]
MAPP	59.300 Hz [9]
NPCC	59.300 Hz [10]
SERC	59.500 Hz [11]
SPP	59.300 Hz [12]

Don McInnis of FPL provided the information regarding FRCC UFLS relays, which, according to information available to PCE at this time, have the highest frequency trigger point to serve its specific needs of handling potential islanding conditions.

Information obtained for the Eastern Interconnection indicates that its FRL_{low} should be 59.820 Hz.

4. Under-frequency Relay Settings for the WECC Interconnection

At the request of PCE, Don Badley of NWPP provided information regarding the WECC Coordinated Off-Nominal Frequency Load Shedding and Restoration Plan [13]. This document indicates that WECC requires automatic firm load shedding when frequency moves below 59.500 Hz. PCE has also obtained information that some BAs, including AIES, in WECC have UFLS relays outside of the WECC-coordinated plan, which likewise activate at 59.500 Hz [18].

PCE also understands that some BAs in WECC have UFLS relays that are triggered at frequencies as high as 59.900 Hz. PCE ignored this trigger setting in establishing FRL_{low} for WECC. WECC load associated with the UFLS relays that are tripped at frequencies higher than 59.500 Hz is considered interruptible, is much smaller than the firm load shed at the setting of 59.500 Hz, and is not part of the WECC-coordinated scheme. However, PCE recommends that the frequency limits developed for this Standard be evaluated to ensure that operation under the Standard will not lead to frequent shedding of loads whose UFLS relays activate above 59.500 Hz, including 59.900 Hz. One approach may include setting FTL_{low} a few tens of mHz higher than 59.900 Hz.

Information obtained for the WECC indicates that its FRL_{low} should be 59.500 Hz.

5. Under-frequency Relay Settings for the ERCOT Interconnection

PCE obtained the most up-to-date ERCOT Operating Guides available through the ERCOT web site (http://www.ercot.com/Participants/OperatingGuides/index.htm). Information available in these documents indicates that firm load in ERCOT will be automatically shed at 59.300 Hz [14]. These documents also indicate that load may be shed at frequencies higher than 59.300 Hz and as high as 59.800 Hz as part of the Emergency Electric Curtailment Plan, but such load is understood to be interruptible.

Information obtained for the ERCOT indicates that its FRL_{low} should be 59.300 Hz.

6. Over-frequency Limits

In order to set the FRL_{high}, the Standard requires the use of the lowest approved high-frequency relay or turbine over-speed settings consistent with the Interconnection’s reliability requirements. Information provided by Don Badley indicates that this limit should be set to 60.500 Hz for WECC. Further research is necessary to obtain sufficiently accurate information for the Eastern Interconnection. The Standard should specify who must provide approval (Standard Developer, NERC, a Region, or RC), which units' relay setting may be considered (type, minimum size, etc.), and refer to a definition of "Interconnection reliability requirements". It is known that a few units in the Eastern Interconnection will trip when frequency moves above 60.300 Hz, but information available to PCE indicates that these units are very small. This report assumes that 60.500 Hz is an adequate initial estimate of FRL_{high}.

VII. Validate the Concept of Using Supply-side Contingencies to Estimate Interconnection Reliability Risk

1. Summary

PCE's understanding of the process for establishing FAL for each Interconnection, gathered from [1] and [5], is as follows. The Standards Developer is to gather information regarding the largest contingencies in that Interconnection. The contingencies are to be sorted from largest to smallest. The Standard Developer should then, using historical generation loss information, establish a set of contingencies that constitutes the size of the power drop that is not expected to be exceeded more than once every 10 years ("Minimum Safe Megawatt Band"). That power drop will then be a result of several events, spaced closely in time, which for establishing FAL_{low} can be generating unit, plant, HVDC line, and HVDC converter trips. The calculated power drop (negative for generation loss events) is to be divided by the Interconnection frequency response, which is also estimated using historical data, to establish the Minimum Safe Frequency Band. That band is to be added to FRL_{low} to calculate FAL_{low}.

2. Determining the Minimum Safe Megawatt Band

PCE found that in order to validate the Standard and calculate a reasonably accurate Minimum Safe Megawatt Band, it needed to consider not only the largest single contingencies, but also all permutations of the significant supply-disruption events possible, attaching a probability to each event.

A great resource for this purpose turned out to be GADS (http://www.nerc.com/~gads). To obtain the necessary information PCE contacted GADS's administrator Michael Curley, who provided data for the past 10 years as reported by utilities in all NERC Regions. This data represents approximately 90% of the generators in the four major Interconnections (Eastern, WECC, ERCOT, and Quebec) and an even more significant percentage of the higher-capacity units, which are the ones most important to this project. Mr. Curley extracted data related to immediate forced unit trips and supplied information regarding the set of generators that may be synchronized to the Interconnection along with their capacity, average output, and service hours.

Using this data PCE calculated the expected trip rate for all types (separated by fuel type as well as hydro) of units and capacity. Additionally, PCE calculated expected trip rates for entire plants of each fuel type by filtering events where multiple units from a single plant tripped within a short interval. PCE then calculated the predicted trip rates for the units and plants likely to be online by using 2003 data to represent the current distribution of generation. The methods used in this analysis are discussed in Appendix A.

PCE then used contingency statistics obtained from this analysis to calculate the expected number of times that a given power drop could occur in the Interconnection as a result of single or multiple events in an interval of 10 years (required by the Standard for determining FAL_{low}). In order to estimate the diminishing impact of multiple events as they become more widely separated in time, PCE introduced a recovery rate for the Interconnection, estimated using historical frequency data. The method for determining recovery rate is described in Appendix D. The results for all Interconnections are provided below. However, it was found that with the relatively high existing recovery rate and the relative rarity of large contingencies for all NERC Interconnections, the value of recovery rate did not have a significant impact on results.

The process and theory produced for the analysis of the occurrence rate of events of a given size, as well as the assumptions and approximations applied in the process, are described in detail in Appendix B.

3. Eastern Interconnection

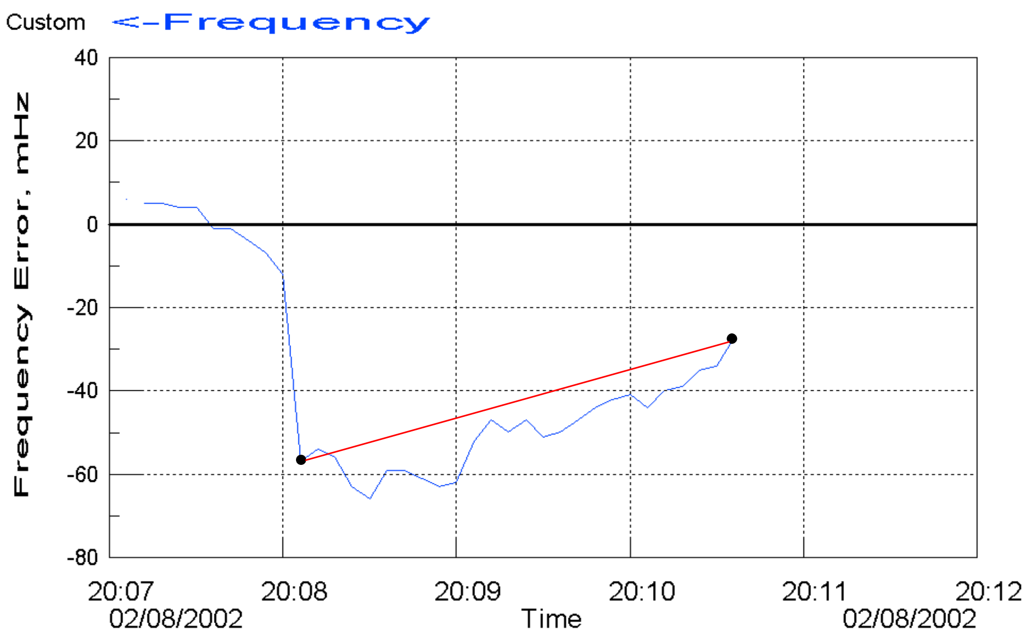

Figure 7. Typical recovery from a contingency in the Eastern Interconnection.

PCE applied the methods detailed in Appendices A and B to GADS data, along with a recovery rate of 807 MW/min, estimated using the method discussed in Appendix D, to calculate a Minimum Safe Megawatt Deadband of 2,750 MW for the Eastern Interconnection.

4. WECC Interconnection

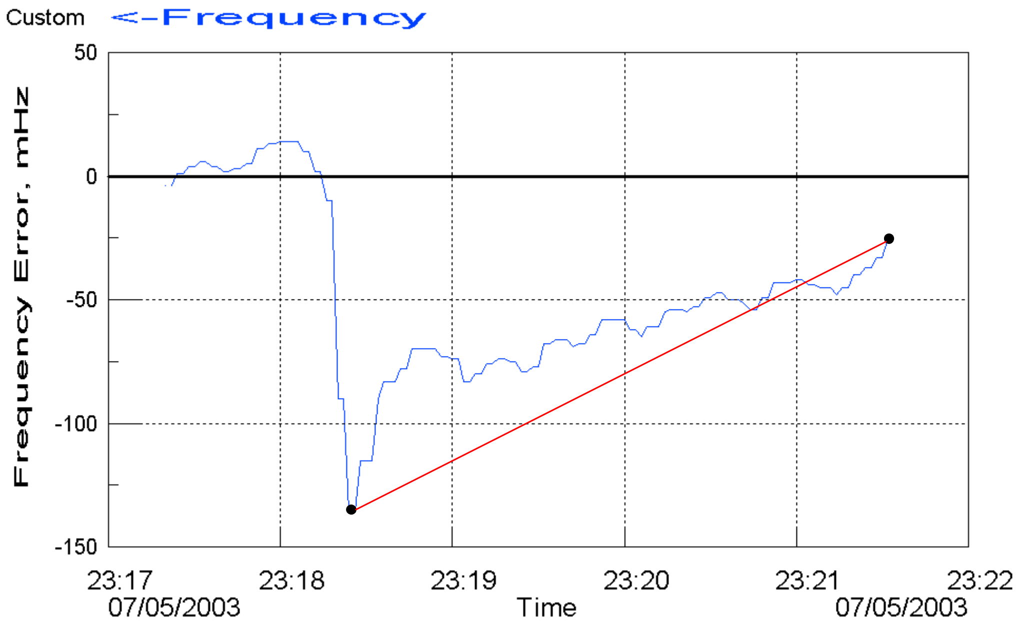

Figure 8. Typical recovery from a contingency for the WECC Interconnection.

PCE applied the methods detailed in Appendices A and B to GADS data, along with a recovery rate of 403 MW/min, estimated using the method discussed in Appendix D, to calculate a Minimum Safe Megawatt Deadband of 2,150 MW for the WECC Interconnection.

The above 2,150 MW does not take into account generation loss associated with RAS or transmission contingencies. WECC has experienced a number of contingencies larger than 2,150 MW due to such causes. According to data provided by Don Badley of NWPP and other sources, the largest power loss in WECC in the past 10 years according to data available to PCE has been about 4,600 MW due to the trip of some transmission facilities. Several contingencies resulting in generation losses of over 2,200 MW caused by RAS activation have also occurred in the past few years (see Figure 4). PCE has found that using such events with the process proposed in the Standard for setting the Minimum Safe Megawatt Deadband results in frequency limits that are extremely conservative or even above 60 Hz, as discussed in section VIII.

5. ERCOT Interconnection

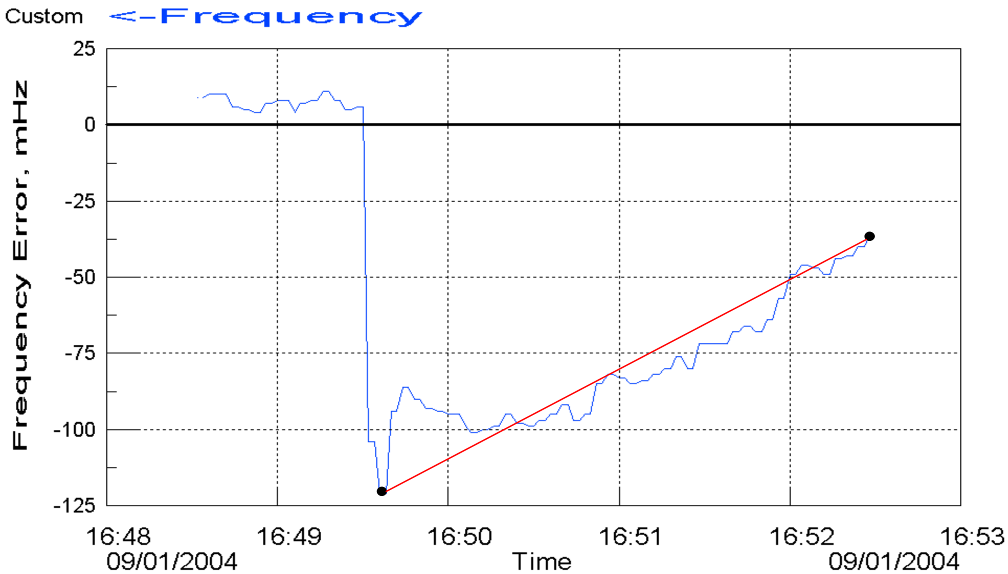

Figure 9. Typical recovery from a contingency in the ERCOT Interconnection.

PCE applied the methods detailed in Appendices A and B to GADS data, along with a recovery rate of 146 MW/min, estimated using the method discussed in Appendix D, to calculate a Minimum Safe Megawatt Deadband of 1,350 MW for the ERCOT Interconnection.

According to the data provided by ERCOT, a multiple-event contingency much larger than 1,350 MW, initiated by a transmission event, was observed in ERCOT during the past 10 years. However, that contingency changed the frequency by more than 700 mHz and, as ERCOT's FRL_{low} is set at 59.300 Hz, it caused some firm load shed (Figure 5 shows the frequency trend associated with this event). Therefore, the impact of a recurrence of such a contingency on UFLS cannot be effectively mitigated without operating the Interconnection above 60 Hz. Moreover, all other contingencies in the 11 years of event data available to PCE are consistent with the Minimum Safe Megawatt Deadband of 1,350 MW stated above. This suggests that, if events resulting in frequency drops close to 700 mHz recur no more often than once every 10 years, proper standards designed to mitigate the impact of smaller contingencies should be sufficient to bound the risk of reaching FRL_{low} to the targeted rate. Following such considerations, PCE chose to use a Minimum Safe Megawatt Deadband of 1,350 MW for the purposes of calculating frequency limits in this report.

6. Using Actual Frequency Data to Verify Results

PCE recommends that future research undertake the task of verifying the results of the process for determining the rate of generation contingencies using available frequency. Frequency data collected at a resolution of about 6 seconds or less over extended periods of time (at least 5-10 years) can be utilized for this purpose. Such a verification process would count the number of times various large power deficiencies occurred over the range of the data, compare that number with the prediction of the method proposed by PCE, and, using statistical tools, calculate the degree of confidence provided by it.

VIII. Validate Steps in Process for Establishing Frequency Limits

1. Summary

The tables in this section present the results obtained by following the process for developing frequency limits specified in [1]. The left column lists the label of the requirement described in the middle column as given in the Standard. The right column describes how the requirement may be followed using data obtained in this project.

This section attempts to only follow the steps of the proposed process for developing frequency limits. Most of the issues regarding the usefulness and validity of the limits derived using this process for the purpose of maintaining Interconnection reliability or of the data used in deriving these limits are discussed in the other sections of this report, particularly sections IV, V, VI, and VII.

2. Determining lower frequency limits

Table 3. Determining lower frequency limits for the Eastern Interconnection.

	Process Specification	**Analysis**
R3.1	Determine the highest approved (firm load) Under Frequency Load Shed (UFLS) relay setting for the Interconnection. This shall be the Interconnection's FRL_{Low}.	Data gathered by PCE and discussed in section VI supports placing FRL_{low} for the Eastern Interconnection at 59.820 Hz.
R3.2	Establish the Interconnection's Frequency Response based on an average of the prior 3 years' data (beta in megawatts per 0.1 hertz).	Research performed by PCE and discussed in section V estimates Eastern Interconnection's P-Frequency-Response to large negative frequency events to be -3,109 MW/0.1Hz.
R3.3	Identify the largest single Contingency events for the Interconnection and order them from largest to smallest.	PCE has done so using data made available by NERC GADS.
R3.4	Determine the number of allowable Contingencies for the Interconnection and sum these Contingencies to determine the low Minimum Safe Megawatt Deadband for the Interconnection.	PCE has created a method to estimate the power drop associated with a once-in-10-years probability, described in section VII, and estimated Minimum Safe Megawatt Deadband to be 2,750 MW.

Table 3. Determining lower frequency limits for the Eastern Interconnection; cont'd.

	Process Specification	Analysis
R3.5	Calculate the frequency change associated with the low Minimum Safe Megawatt Deadband for the Interconnection by dividing the low Minimum Safe Megawatt Deadband in megawatts by the Frequency Response of the Interconnection in megawatts per hertz. This is the low Minimum Safe Frequency Deadband for the Interconnection.	Using the estimates discussed above the Minimum Safe Frequency Deadband is equal to 2,750 MW/(-10*-3,109 MW/0.1Hz) = 0.088 Hz.
R3.6	Calculate the Interconnection's FAL_{Low} by adding the low Minimum Safe Frequency Deadband to the highest approved UFLS relay setting for the Interconnection.	Using the estimates above places FAL_{low} for the Eastern Interconnection at 59.820 Hz + 0.088 Hz = 59.908 Hz.
R3.7	Calculate the FTL_{Low} by adding the next largest single Contingency to the FAL_{Low}.	The proposed process indicates that the largest contingency not considered in step R3.4 should be used to calculate the FTL_{low}. A large plant trip would add an additional contingency of well over 2,000 MW. If we limit the definition of "single contingency" to unit trips, as NERC has done in other standards, the additional contingency would be approximately 1,300 MW. BRD SDT accepted this approach. The Standard should be modified to clarify which contingencies should be considered. Use of 1,300 MW as the next contingency puts FTL_{low} at 59.908 Hz + 1,300 MW/(-10*-3,109 MW/0.1Hz) = 59.950 Hz.
R3.8	Establish the FTL's T_v by determining the time at which the probability of a second Contingency exceeds acceptable limits.	BRD SDT has directed that this should be interpreted as: "set T_{vfl} to be the time interval at which the probability of a next largest single contingency generator trip is equal to 50%". PCE estimated the average expected time between generation contingencies of 1,300 MW or higher, and found it to be 26.4 days. As directed by the Standard, T_{vfl} has been limited to a maximum of 30 minutes.

Table 4. Determining lower frequency limits for the WECC Interconnection.

	Process Specification	Analysis
R3.1	Determine the highest approved (firm load) Under Frequency Load Shed (UFLS) relay setting for the Interconnection. This shall be the Interconnection's FRL_{Low}.	Data gathered by PCE and discussed in section VI supports placing FRL_{low} for WECC at 59.500 Hz.
R3.2	Establish the Interconnection's Frequency Response based on an average of the prior 3 years' data (beta in megawatts per 0.1 hertz).	Research performed by PCE and discussed in section V estimates WECC Interconnection's P-Frequency-Response to large negative frequency events to be -969 MW/0.1Hz.
R3.3	Identify the largest single Contingency events for the Interconnection and order them from largest to smallest.	PCE has done so using data made available by NERC GADS.
R3.4	Determine the number of allowable Contingencies for the Interconnection and sum these Contingencies to determine the low Minimum Safe Megawatt Deadband for the Interconnection.	PCE's estimate using GADS data of independent generation contingencies and the method described in section VII indicates a necessary Minimum Safe Megawatt Deadband of approximately 2,150 MW. Consideration of generation losses associated with RAS or transmission contingencies substantially increases the above deadband. The largest power loss in WECC in the past 10 years according to data available to PCE has been about 4,600 MW due to the trip of some transmission facilities. Many other events have occurred that resulted in a power loss of more than 2,150 MW (see Figure 4).
R3.5	Calculate the frequency change associated with the low Minimum Safe Megawatt Deadband for the Interconnection by dividing the low Minimum Safe Megawatt Deadband in megawatts by the Frequency Response of the Interconnection in megawatts per hertz. This is the low Minimum Safe Frequency Deadband for the Interconnection.	Based on only independent generation trips and ignoring RAS as well as transmission-related contingencies the Minimum Safe Frequency Deadband is estimated to be 2,150 MW/(-10*-969 MW/0.1Hz) = 0.222 Hz. However, considering generation losses associated with RAS or transmission contingencies substantially increases the above frequency deadband. The largest frequency drop in WECC in the past 10 years according to data available to PCE has been 0.443 Hz due to the trip of some transmission facilities.

Table 4. Determining lower frequency limits for the WECC Interconnection; cont'd.

	Process Specification	Analysis
R3.6	Calculate the Interconnection's FAL $_{Low}$ by adding the low Minimum Safe Frequency Deadband to the highest approved UFLS relay setting for the Interconnection.	Using the estimates above, if RAS as well as transmission-related contingencies are ignored, FAL_{low} for the WECC Interconnection would be set about 59.500 Hz + 0.222 Hz = 59.722 Hz. Depending on which losses due to RAS and transmission events must also be considered, FAL_{low} could be set as high as 59.943 Hz.
R3.7	Calculate the FTL_{Low} by adding the next largest single Contingency to the FAL_{Low}.	If we limit the contingencies considered for computing FTL_{low} to unit trips, as was accepted by BRD SDT in Phase I for the Eastern Interconnection, the additional contingency would be approximately 1,300 MW. Using the latter estimate and ignoring generation losses associated with RAS and transmission contingencies would put FTL_{low} at 59.722 Hz + 1,300 MW/(-10*-969 MW/0.1Hz) = 59.856 Hz. Depending on which losses due to RAS and transmission events must also be considered, FTL_{low} could be as high as 60.075 Hz. To satisfy CPM-1 with ε_1 = 22.8 mHz in WECC frequency should rarely wander beyond the range of 70 mHz to 90 mHz away from scheduled frequency. Hence, when it reaches these levels a coordinated action would be beneficial to expedite its return to the normal range. Thus, it is beneficial to set FTL about 3 or 4 times ε_1 from scheduled frequency. This should also prevent substantial increase in the rate of shedding of non-firm loads.
R3.8	Establish the FTL's T_v by determining the time at which the probability of a second Contingency exceeds acceptable limits.	BRD SDT has directed that this should be interpreted as: "set T_{vfl} to be the time interval at which the probability of a next largest single contingency generator trip is equal to 50%". PCE estimated the average expected time between generation contingencies of 1,300 MW or higher and found it to be 131.0 days. As directed by the Standard, T_{vfl} has been limited to a maximum of 30 minutes.

Table 5. Determining lower frequency limits for the ERCOT Interconnection.

	Process Specification	Analysis
R3.1	Determine the highest approved (firm load) Under Frequency Load Shed (UFLS) relay setting for the Interconnection. This shall be the Interconnection's FRL_{Low}.	Data gathered by PCE and discussed in section VI supports placing FRL_{low} for ERCOT at 59.300 Hz.
R3.2	Establish the Interconnection's Frequency Response based on an average of the prior 3 years' data (beta in megawatts per 0.1 hertz).	Research performed by PCE and discussed in section V estimates ERCOT Interconnection's P-Frequency-Response to large negative frequency events to be -419 MW/0.1Hz.
R3.3	Identify the largest single Contingency events for the Interconnection and order them from largest to smallest.	PCE has done so using data made available by NERC GADS.
R3.4	Determine the number of allowable Contingencies for the Interconnection and sum these Contingencies to determine the low Minimum Safe Megawatt Deadband for the Interconnection.	PCE has created a method to estimate the power drop associated with a once-in-10-years probability, described in section VII, and estimated Minimum Safe Megawatt Deadband to be 1,350 MW.
R3.5	Calculate the frequency change associated with the low Minimum Safe Megawatt Deadband for the Interconnection by dividing the low Minimum Safe Megawatt Deadband in megawatts by the Frequency Response of the Interconnection in megawatts per hertz. This is the low Minimum Safe Frequency Deadband for the Interconnection.	Based on only independent generation trips and ignoring transmission-related contingencies the Minimum Safe Frequency Deadband is estimated to be 1,350 MW/(-10*-419 MW/0.1Hz) = 0.322 Hz. Note: If generation losses due to transmission contingencies are also considered, the largest frequency drop in ERCOT in the past 10 years according to data available to PCE has been 0.729 Hz. However, as an event of this magnitude appears to have an occurrence rate smaller than one in ten years and is larger than the difference between 60 Hz and FRL_{low}, it should not be used to set FAL_{low}.

Table 5. Determining lower frequency limits for the ERCOT Interconnection; cont'd.

	Process Specification	**Analysis**
R3.6	Calculate the Interconnection's FAL_{Low} by adding the low Minimum Safe Frequency Deadband to the highest approved UFLS relay setting for the Interconnection.	FAL_{low} for the ERCOT Interconnection is calculated as 59.300 Hz + 0.322 Hz = 59.622 Hz from the estimates above.
R3.7	Calculate the FTL_{Low} by adding the next largest single Contingency to the FAL_{Low}.	If we limit the contingencies under consideration here to unit trips, as was accepted by BRD SDT in Phase I for the Eastern Interconnection, the additional contingency would be approximately 1,300 MW. Using the latter estimate puts FTL_{low} at 59.622 Hz + 1,300 MW/(-10*-419 MW/0.1Hz) = 59.932 Hz.
R3.8	Establish the FTL's T_v by determining the time at which the probability of a second Contingency exceeds acceptable limits.	BRD SDT has directed that this should be interpreted as: "set T_{vfl} to be the time interval at which the probability of a next largest single contingency generator trip is equal to 50%". PCE estimated the average expected time between generation contingencies of 1,300 MW or higher and found it to be 91.3 days. As directed by the Standard, T_{vfl} has been limited to a maximum of 30 minutes.

3. Determining upper frequency limits

Determination of upper frequency limits has not been within the scope of the research to this point. Below is an example of following the proposed process using provisional data. In some cases, such as the magnitude of the contingency for choosing FTL, sample values were used, which may be significantly different from those derivable from empirical data.

Table 6. Determining upper frequency limits for the Eastern Interconnection.

	Process Specification	**Analysis**
R4.1	Determine the lowest approved high frequency relay or turbine overspeed setting for the Interconnection consistent with the Interconnection's reliability requirements. This shall be the Interconnection FRL_{High}.	Preliminary data gathered by PCE supports placing FRL_{high} for the Eastern Interconnection at 60.500 Hz.
R4.2	Determine the Frequency Response of the Interconnection as calculated above for the interconnection low frequency limits.	Provisionally, for the purpose of evaluating the process, PCE used data available for all (negative and positive) frequency events to estimate the P-Frequency-Response of the Eastern Interconnection as related to high frequency limits. Preliminary data gathered by PCE indicates that Eastern Interconnection's P-Frequency-Response to such frequency events is 3,180 MW/0.1Hz.
R4.3	Identify the largest high frequency producing Contingency events for the Interconnection and order them from largest to smallest.	PCE has done that using data from Elmer Bourque of NBP.

Table 6. Determining upper frequency limits for the Eastern Interconnection; cont'd.

	Process Specification	Analysis
R4.4	Determine the number of allowable Contingencies for the Interconnection as discussed above and sum these Contingencies to determine the upper Minimum Safe Megawatt Deadband for the Interconnection.	While it is not immediately clear what data can be used to estimate the Maximum Allowable Frequency Rise defined in the proposed process, PCE believes that in the past 10 years the largest single event has been the partial blackout on August 14, 2003. PCE has used this event to make a preliminary estimate. However, PCE understands that UFLS relay activation occurring as a result of a separation of a large portion of the Interconnection does not count toward violating the one-in-10-years targeted rate.
R4.5	Calculate the frequency change associated with the Minimum Safe Megawatt Deadband High for the Interconnection by dividing the sum of the allowable Contingencies (in megawatts) by the Frequency Response (in megawatts per hertz). This gives you the high Minimum Safe Frequency Deadband for the Interconnection.	A fast time error correction was in effect when the northeast portion separated from the Eastern Interconnection on August 14, 2003. Data shows that, upon this separation, frequency error reached a peak of about 0.299 Hz in the intact portion of the Eastern Interconnection. This frequency rise will be used as the working and very conservative estimate of Minimum Safe Frequency Deadband for evaluating this process.
R4.6	Calculate the high Interconnection's FAL by subtracting the high Minimum Safe Frequency Deadband from the lowest approved reliability-related high frequency relay setting for the Interconnection.	Using the above preliminary estimate of the Maximum Allowable Frequency Rise, FAL_{high} will be set to 60.500 Hz – 0.299 Hz = 60.201 Hz.

Table 6. Determining upper frequency limits for the Eastern Interconnection; cont'd.

	Process Specification	Analysis
R4.7	Calculate the FTL_{High} by adding the next largest single Contingency to the FAL_{High}.	A load loss of 1,000 MW will be used as the sample contingency for this step. However, PCE does not see a statistical justification for using a contingency of any particular size in this calculation and believes that this step in the process needs to be modified to have a solid theoretical foundation. Using this preliminary estimate puts FTL_{high} at 60.201 Hz – 1,000 MW/(3,180 MW/0.1Hz) = 60.170 Hz. To satisfy CPM-1 with ε_1 = 18 mHz in the Eastern Interconnection frequency should rarely wander beyond the range of 50 mHz to 70 mHz away from scheduled frequency. Hence, when it reaches these levels a coordinated action would be beneficial to expedite its return to the normal range. On this basis, it is beneficial to limit FTL setting to about 3 or 4 times ε_1 away from scheduled frequency.
R4.8[1]	Establish T_v for the FTL_{High} by determining the time at which the probability of a second Contingency exceeds acceptable limits.	No specific method has been established to set T_{vfh}.

4. Conclusions and Recommendations

Sufficient data exists to establish the low frequency limits using the method proposed by BRD SDT. However, if all possible contingencies are considered, the proposed process may result in an FTL_{low} very close to or greater than 60 Hz for WECC. On the other hand, if some contingencies are arbitrarily excluded, the proposed process could yield limits that may not adequately prevent undesirable operation in the Interconnection. BRD SDT may need to consider alternative approaches for setting frequency limits that result in reasonable values and maintain reliable operation.

Generally, it is a good idea to attempt to realize about the same probability distribution for frequency as it has recently been realized. This is in line with the directive specified in the SAR to maintain the existing frequency profile. In order to accomplish this it is important to arrest frequency deviations that exceed 3 or 4 times ε_1. This approach may also be useful for setting high frequency limits. Although additional sources of data and research may be necessary to

[1] This step is mislabeled "R5" in Draft 4 of the Standard.

establish the high frequency limits, preliminary analysis in section VIII.3 indicates that maintaining the frequency profile may become the controlling consideration for setting frequency limits when frequency error is positive.

PCE recommends that BRD SDT modify the name of different T_v values to reflect their different meanings and ease communication, even if their values are initially selected to be equal to each other. One approach is to use the names T_{vb}, T_{vfl}, T_{vfh}, defined in this report.

PCE recommends that further research be performed to establish a more technically defensible process for calculating T_{vfl} and T_{vfh}.

IX. Validate the Steps in the Process for Developing BAALs

1. Summary

PCE understands that the portion of the Standard relevant to BAs requires that they continuously calculate the BAAL applicable to them. The Standard also suggests penalizing any BA whose ACE is beyond its BAAL for T_{vb} contiguous minutes.

The proposed BAAL formulation ensures that if frequency is beyond FTL, then at least one BA is beyond its associated BAAL. Thus, returning all BAs' ACE within the BAAL is sufficient for returning frequency within FTL. Many ACE limit formulations besides the proposed one would have this property.

PCE analysis also found that the proposed BAAL equation is based on an assumption that a linear relationship exists between the current product of a BA's ACE and frequency error, and its contribution to the risk of the Interconnection exceeding under- or over-frequency limits. PCE did not find justification for making this assumption.

2. BAAL Formulation

The Standard specifies that BAAL will be calculated as follows:

$$BAAL_{low,i} = (-10B_i \times (FTL_{low} - F_S)) \times \frac{(FTL_{low} - F_S)}{(F_A - F_S)} \quad when\ F_A < F_S \qquad \text{(IX-1)}$$

$$BAAL_{high,i} = (-10B_i \times (FTL_{high} - F_S)) \times \frac{(FTL_{high} - F_S)}{(F_A - F_S)} \quad when\ F_A > F_S \qquad \text{(IX-2)}$$

where,

$BAAL_{low,i}$ is the low BAAL for BA *i*.

$BAAL_{high,i}$ is the high BAAL for BA *i*.

B_i is the frequency bias for BA *i*.

F_S is the scheduled frequency for the interconnection.

F_A is the official measured frequency for the interconnection.

As shown below, if the ACE of each BA in the Interconnection is greater than the $BAAL_{low}$ of that BA, then the Interconnection frequency must be greater than FTL_{low}. Note that for the purpose of the discussion below, we take F_A to be less than F_S because the $BAAL_{low}$ equation (IX-1) is applicable only when $F_A < F_S$.

Assume that:

For each BA *i*, $ACE_i > BAAL_{low,i}$ (IX-3)

Replacing the right hand side with the equation defined for $BAAL_{low,i}$ in (IX-1) gives:

$$\text{For each } i,\ ACE_i > (-10B_i \times (FTL_{low} - F_S)) \times \frac{(FTL_{low} - F_S)}{(F_A - F_S)} \qquad \text{(IX-4)}$$

Summing across all *I* BAs in the Interconnection:

$$\sum_{i=1}^{I} ACE_i > \sum_{i=1}^{I} (-10B_i \times (FTL_{low} - F_S)) \times \frac{(FTL_{low} - F_S)}{(F_A - F_S)} \qquad \text{(IX-5)}$$

Moving the constant factors outside the summation on the right-hand side:

$$\sum_{i=1}^{I} ACE_i > \frac{(FTL_{low} - F_S)^2}{(F_A - F_S)} \times \sum_{i=1}^{I} -10B_i \qquad \text{(IX-6)}$$

Dividing both sides by the summation of $-10B_i$ (a positive number):

$$\frac{\sum_{i=1}^{I} ACE_i}{\sum_{i=1}^{I} -10B_i} > \frac{(FTL_{low} - F_S)^2}{(F_A - F_S)} \qquad \text{(IX-7)}$$

In the absence of errors, the sum of ACEs divided by the sum of $-10B_i$ equals frequency error:

$$(F_A - F_S) > \frac{(FTL_{low} - F_S)^2}{(F_A - F_S)} \qquad \text{(IX-8)}$$

Multiplying both sides by $F_A - F_S$; since $F_A - F_S < 0$, we must reverse the inequality:

$$(F_A - F_S)^2 < (FTL_{low} - F_S)^2 \qquad \text{(IX-9)}$$

Dividing both sides by $(FTL_{low} - F_S)^2$:

$$\frac{(F_A - F_S)^2}{(FTL_{low} - F_S)^2} < 1 \qquad \text{(IX-10)}$$

Taking square root of both sides; we only follow the plus side of the root, since the minus side for the conditions under study is inapplicable:

$$\frac{F_A - F_S}{FTL_{low} - F_S} < 1 \qquad \text{(IX-11)}$$

Multiplying both sides by $FTL_{low} - F_S$; since $FTL_{low} - F_S < 0$, we must reverse the inequality:

$$F_A - F_S > FTL_{low} - F_S \qquad \text{(IX-12)}$$

Adding F_S to both sides, we reach the conclusion:

$$F_A > FTL_{low} \qquad \text{(IX-13)}$$

With the assumption made in (IX-3), i.e. $ACE_i > BAAL_{low,i}$ for every BA, the above relation shows that the frequency will be greater than FTL_{low}. Following the same argument, the condition of $ACE_i > BAAL_{low,i}$ may not be true for every BA if F_A turns out to be lower than FTL_{low}. Therefore, if F_A is lower than FTL_{low}, then ACE_i for at least one of the BAs must be lower than $BAAL_{low,i}$.

A similar relationship can be shown to exist between F_A, FTL_{high}, ACE_i, and $BAAL_{high,i}$. On this basis, we conclude that if frequency is beyond the range of FTL_{low} to FTL_{high}, then ACE_i for at least one BA is beyond its associated BAAL, and returning ACE_i of all such BAs within the range of $BAAL_{low,i}$ to $BAAL_{high,i}$ is sufficient for returning frequency within the range of FTL_{low} to FTL_{high}. These properties may provide some benefits to the RC in their task of maintaining reliable operation.

The above properties are not, however, unique to the proposed formulation of BAAL. Many formulations for BAAL have the same properties. Among others, any formula that is i) a monotonously decreasing function of frequency when frequency is less than F_S and ii) equal to $-10B_i \times (FTL - F_S)$ when frequency is equal to the FTL, has the same properties.

During periods of time error correction, the proposed BAAL equations (IX-1) and (IX-2) give an excessively tight limit in one direction. As a remedy, BRD SDT has discussed the idea of allowing F_S in these equations to remain at 60 Hz in such periods. It should be noted that the properties mentioned above for BAAL will no longer hold during time error correction if scheduled frequency is replaced with 60 Hz in (IX-1) and (IX-2).

3. Relationship between Frequency Error and Risk of Reaching FRL

PCE understands that the BAAL equation has been developed with the idea that it should designate an acceptable amount of risk of reaching FRL a BA should be allowed to contribute to the Interconnection and penalize the BA should it contribute any additional risk [2]. Specifically, for the high frequency side, the Standard encourages each BA *i* to maintain:

$$ACE_i \le BAAL_{high,i} = (-10B_i \times (FTL_{high} - F_S)) \times \frac{(FTL_{high} - F_S)}{(F_A - F_S)} \qquad \text{(IX-14)}$$

Multiplying all terms of the above condition by $F_A - F_S$ gives the following:

$$ACE_i \times (F_A - F_S) \le BAAL_{high,i} \times (F_A - F_S) = -10B_i \times (FTL_{high} - F_S) \times (FTL_{high} - F_S) = R_{\max} \qquad \text{(IX-15)}$$

where R_{max} is the same as the M_R value introduced in [2] and interpreted as the <u>maximum risk of reaching FRL</u> that a BA is allowed to impose on the Interconnection at any given frequency error. The condition above assumes that we are bounding *R*, the risk described by the product of ACE and frequency error below, by a maximum value:

$$ACE_i \times (F_A - F_S) = R \le R_{\max} \qquad \text{(IX-16)}$$

Condition (IX-17), used as a basis for the Standard, implies that for a given ACE the risk contributed by a BA to the Interconnection is proportional to $F_A - F_S$, or $R \sim F_A - F_S$. In other words, the risk imposed on the Interconnection of exceeding a given FRL by operating at a given frequency is proportional to the difference between that frequency and scheduled frequency.

PCE research has shown that the above-defined risk formulation is not strongly correlated with the probability of exceeding the FRL over a specified future period of time (e. g. 10 years). An index that describes such a risk is more likely related to the inverse of the power change in the balance between resources and demand needed to move the frequency to FRL. Therefore the risk may be related to the inverse of the difference between FRL and the current frequency, $1/\left(FRL - F_A\right)$.

The implied risk in (IX-16) can be challenged using a couple of simple examples. If FRL_{high} for the Eastern Interconnection is set at 60.500 Hz and scheduled frequency is 60 Hz, condition (IX-16) evaluates the risk imposed on the Interconnection by a given BA ACE at frequency errors of 5 mHz and 10 mHz to, respectively, to be:

$$R_{60.005Hz} = ACE \times (60.005 - 60.000) = 0.005 \times ACE \qquad \text{(IX-17)}$$

$$R_{60.010Hz} = ACE \times (60.010 - 60.000) = 0.010 \times ACE \qquad \text{(IX-18)}$$

However, it is apparent that the frequency change due to contingencies or other causes required in these two cases to take Interconnection frequency to FRL = 60.500 Hz, i.e. 495 mHz for frequency error 5 mHz and 490 mHz for 10 mHz, have a ratio close to 1. As seen above, however, the risk implied by the BAAL equation in the latter case is twice that of the former case. More importantly, condition (IX-16) implies:

$$R_{60.400Hz} = ACE \times (60.400 - 60.000) = 0.400 \times ACE \qquad \text{(IX-19)}$$

$$R_{60.450Hz} = ACE \times (60.450 - 60.000) = 0.450 \times ACE \qquad \text{(IX-20)}$$

The two equations above imply that the risk of the frequency exceeding 60.500 Hz is not significantly different between the cases where frequency error is 400 mHz and 450 mHz. However, it is clear that the latter case requires only half the contingency size of the former to bring the Interconnection to the critical point, which is likely to happen more than twice as often and carries therefore more than twice the probability and twice the risk. This can be shown from study of the frequency error change distribution or the generation contingency analysis discussed in Appendix B.

As discussed above, it can be shown that the risk of exceeding FRL is related to the inverse of the difference between that FRL and the current frequency. The details of such a relationship are complex, but PCE believes that statistical analysis can be used to establish a statistically defensible method, which results in a measure that is easily understandable and can be functionally applied in operations.

X. Validate that the Balancing Authority ACE Limits Work as Intended

1. Summary

This section provides examples to show how the probability of an aggregate report of several BAs is generally much less likely to violate the Standard than the individual report of any single member BA. This observation was partly inspired by the results of the CERTS report, provided to BRD SDT, on the number of times BAAL were exceeded based on historical data from the NERC-CERTS ACE-Frequency Monitoring system for 80 BAs in the Eastern Interconnection. The effect of this conclusion is that the burden of controlling using BAAL measures may fall disproportionately on the smaller BAs. Based on preliminary analysis, as illustrated in the example scenarios, PCE recommends that the proposed BA measures be the subject of more extensive mathematical research.

In attempting to establish T_{vb} associated with the BAALs, PCE tried to estimate how Interconnection frequency may behave once some BAs exceed or are close to exceeding those BAALs. However, PCE does not believe that sufficient information is available to reliably evaluate the risk of reaching FRL associated with a particular T_{vb} under the measures specified by the Standard.

2. Relationship between BAAL-based measures and Safe Operation

PCE attempted to examine the effect of the proposed BAAL measures on Interconnection frequency. The following examples illustrate some discrepancies between BAAL measures and reliability.

In all scenarios shown below the BA under consideration is the same. We also assume that the BAAL trend, shown in red in the figures below, for the BA under consideration is the same. Therefore, the frequency trend in the Interconnection is also the same in all of the scenarios.

In scenario A (Figure 10), the BA fails to return ACE above its BAAL in time to satisfy the T_{vb} time limit:

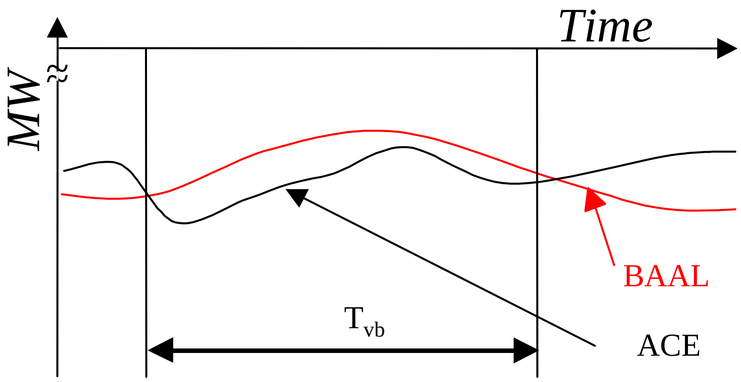

Figure 10. Example scenario of a BA failing BAAL measure.

In scenarios B (Figure 11) and C (Figure 12) the BA satisfies the T_{vb} time limit. In scenario B, it operates with a very negative ACE for an extended period of time, particularly when frequency error magnitude becomes very large. In scenario C, it operates with a negative ACE that exceeds its BAAL for a time interval shorter than T_{vb}, then for a period of time bounds its ACE to its BAAL, but then its ACE exceeds its BAAL in the same T_{vb} interval again.

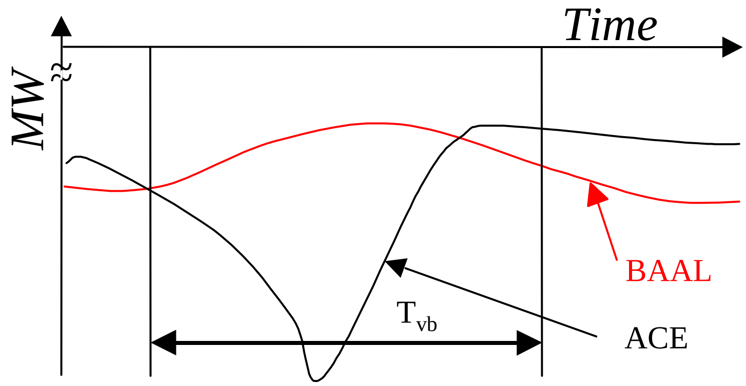

Figure 11. Example scenario of a BA introducing a great deal of risk to the Interconnection while not violating the BAAL measures.

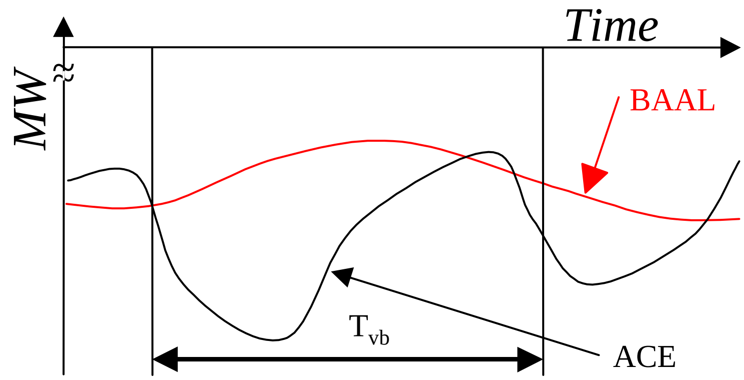

Figure 12. Example scenario of a BA introducing a great deal of risk to the Interconnection while not violating the BAAL measures.

PCE believes that in scenarios B and C the risk of reaching FRL imposed on the Interconnection by the BA is greater than in scenario A. This creates a difficulty in definitively evaluating the risk contributed to the Interconnection at a given frequency by a given BA and raises the question whether a T_{vb} that adequately protects the Interconnection in all situations without imposing undue control requirements can be determined.

PCE believes that the proper measure should be able to adequately evaluate the risk of reaching FRL imposed on the Interconnection by BAs. One alternative idea for measuring performance is finding the average of that risk, measured as a function of ACE and frequency, over a short targeted interval, and penalizing BAs that exceed a predefined limit in that interval.

3. Example of the Effect of Aggregate Reporting on Expected Number of BAAL Violations

PCE believes that for the current setting of FTL_{low}, it is probable that the BAAL measures will create fewer violations for any set of BAs if those BAs report their ACE aggregately. Under the proposed BAAL measures, a BA cannot compensate less-than-acceptable performance in one period with a performance in excess of the requirements in another period. However, if two BAs combine, it is likely that there will be occasions where one performs in excess of the requirements when, at the same time, the performance of the other does not meet the requirements. In some such cases, the aggregate performance will eliminate a violation.

Figure 13 shows, over two one-hour windows, a performance of two hypothetical BAs, each with a frequency bias of -100 MW/0.1 Hz. These BAs are part of an interconnection with a total frequency bias of -6,600 MW/0.1 Hz. The ACE trends of BAs "A" and "B" are plotted in green and purple, respectively. The arrows next to the labels for these trends are pointing to the left; this means that their trends are plotted against the MW axis shown on the left.

In the left window, the ACE of BA "B" remains zero throughout the hour while the ACE of BA "A" varies and includes a ramp down, a flat portion, and a ramp up. On the right window, the ACE of BA "A" remains zero while the ACE of BA "B" varies exactly the same way as the ACE of BA "A" varies in the left window.

The sum of the ACEs of all BAs excluding the two BAs under consideration remains constant and identical in both time windows. Thus, the changes in the ACEs of the two BAs are the only reasons for the frequency error variation in each time window, shown in blue, and the $BAAL_{low}$ trend, shown in red. The frequency trend in these two time windows is identical due to the stated assumptions and is plotted against the right axis in both windows.

Only one $BAAL_{low}$ trend is shown in each time window, as these two BAs have the same frequency bias. This trend is in red. On 6/3, BA "A" incurs a violation, as shown in the left window. On 6/20, BA "B" incurs a violation as shown in the right window.

Figure 14 considers a scenario where BAs "A" and "B", discussed above, provide an aggregate performance report to NERC by summing their ACEs and comparing the result with the aggregate BAAL. The aggregate report will naturally use the same frequency trend as plotted in Figure 13 to compute aggregate BAAL. The frequency trend for each time window is re-plotted in Figure 14 in blue.

The aggregate ACE used for report to NERC in each time window is shown in light purple against a larger MW scale on the left axis in Figure 14. $BAAL_{low}$, shown in olive, doubled for the combined BA, as its bias coefficient is twice the individual bias coefficient of its members and the trend of frequency in each time window is the same as that shown in Figure 13. As shown in Figure 14, the aggregate ACE does not even reach BAAL, much less exceed it for T_{vb}. The aggregating BA manages to mask the violations that otherwise would be incurred by each member BA, not by changing their control in a way that reduces risk to the Interconnection, but simply by providing an aggregate report for the two member BAs.

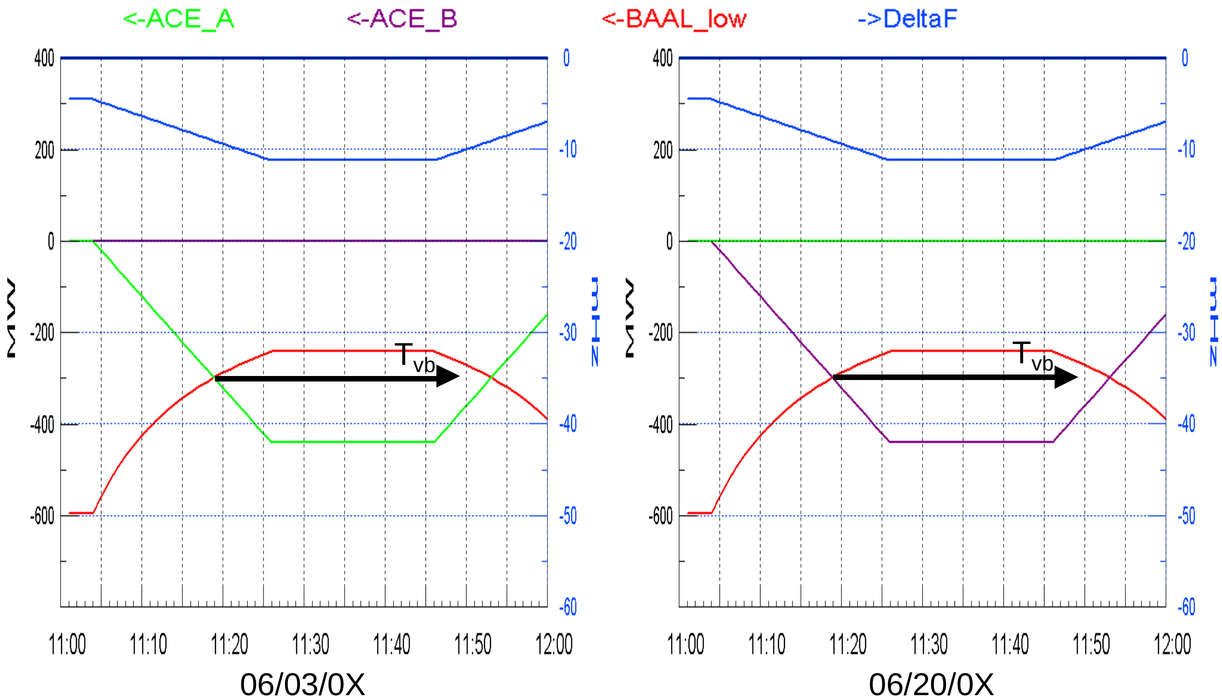

Figure 13. ACE trends of two BAs in two different one-hour periods when separately compared with each BA's $BAAL_{low}$.

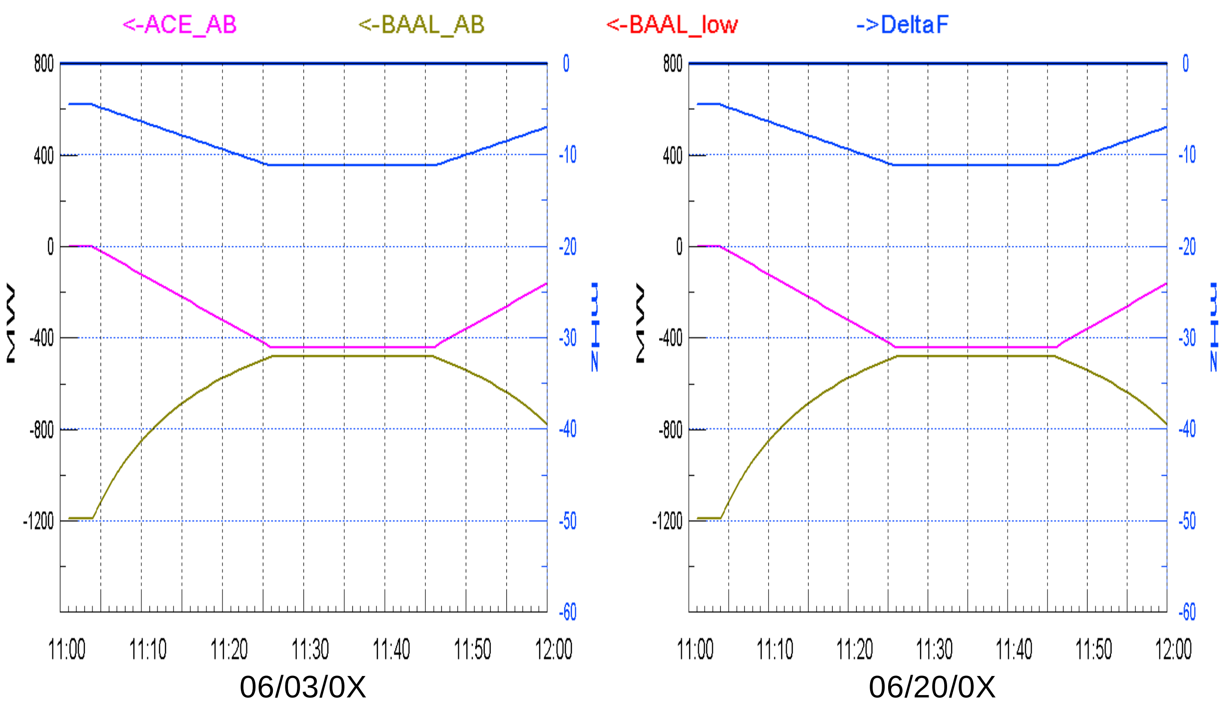

Figure 14. Combined ACE trend of the two BAs in Figure 13 when compared with the $BAAL_{low}$ for the aggregating BA.

In this case the situation with one violation per BA is changed to a situation with zero violations per BA through aggregate reporting. There are also examples where the number of violations per BA can be shown to remain the same or even increase. Tentative analysis by PCE, however, indicates that the cases where the number of violations increases as frequency bias increases are rarer than the cases where the number of violations decreases. The probability of each of these outcomes may be impacted by the value of FTL, but preliminary investigation of historical data and theoretical estimates indicate that the above statement is true for the setting of FTL proposed for the Eastern Interconnection. PCE recommends that the relationship of frequency bias and violations be the subject of further theoretical and empirical research.

Historical data supports the idea that aggregate reporting provides benefits to BAs as their combined frequency bias increases. CERTS analysis of the NERC-CERTS ACE-frequency data provided by 80 Eastern Interconnection BAs for the entire year 2004 showed that, on average, for each BA the one-minute average of ACE exceeded the one-minute average of $BAAL_{low}$ 4,407 times [17]. However, PCE analysis of the frequency data for the same year indicates that the one-minute averages of Eastern Interconnection frequency exceeded FTL_{low} only about 500 times. Moreover, if all BAs in the Eastern Interconnection submitted one aggregate report, the combined entity would not have incurred any violations in any of the past three years, in comparison to the 52 total violations recorded in 2004 just by the BAs reporting their ACE to the NERC-CERTS database. Since many of the 52 violations were incurred by BAs with smaller values of frequency bias, it seems likely that such BAs will also be required to expend a disproportionate amount of effort to maintain acceptable levels of compliance with BAAL.

The fact that smaller BAs need, on average, to exert less effort to control to CPS2 than larger BAs does not affect the results described above. It is true that the control performance measures applicable during the period analyzed by CERTS affected the control decisions made by all BAs. To avoid this issue, however, PCE compared the performance of a number of BAs, taken individually, with the performance of same BAs taken as an aggregate reporting entity. In other words, the actual control decisions were identical for both cases, eliminating any possible impact from CPS2 or any other influence other than aggregation and increased size. The results showed a decrease in the number of failures with increasing BA size.

To summarize, PCE has seen some evidence at this point to indicate that, given reasonably wide settings of FTL, i) BAs with a smaller frequency bias will experience more violations while applying proportionally the same amount of control as BAs with a larger frequency bias and ii) will be required to perform disproportionately more control to achieve the same number of violations as BAs with a larger frequency bias. If this conclusion is valid, it also indicates that the proposed BAAL measures may not fully take diversity into account and imposes unnecessary control even on large BAs, although to a lesser degree than the small ones. A method of dispensing responsibility among BAs is only technically sound (and fair) if the level of required control to satisfy the resulting measure is the same whether or not the BA reports its performance individually or as a part of an aggregated entity. Preliminary analysis discussed above, if verified by further research, would indicate that BAAL measures do not fit that criterion.

XI. Other Considerations

1. Impact of Generation Control Practice

PCE would like to note that its analysis of frequency events indicates that sudden losses of generation and load constitute only a portion of large frequency excursions. PCE suggests that Interconnection power deficiencies that are imposed through generation control and business practices create additional risk. The increase in risk is especially uncertain taking into account how practices may change as a result of the implementing the Standard.

This premise is supported by the data available for this project. Using NERC-CERTS one-minute average frequency database, CERTS staff identified every instance from 1/1/2003 to 12/31/2003 and from 5/12/04 to 9/10/04 where magnitude of frequency error in the Eastern Interconnection from schedule exceeded 50 mHz. PCE also obtained Eastern Interconnection frequency event data from Elmer Bourque of NBP, which is believed to be a fairly comprehensive listing of sudden large frequency changes. Of the 206 separate frequency excursions PCE identified in the period from 5/12/04 to 9/10/04, PCE found only 2 that were noted in Mr. Bourque's data as contingencies. The rest did not show a signature of a sudden change in frequency expected after a generation loss and were apparently a result of generation control practice. The example shown in Figure 15 is representative of that category:

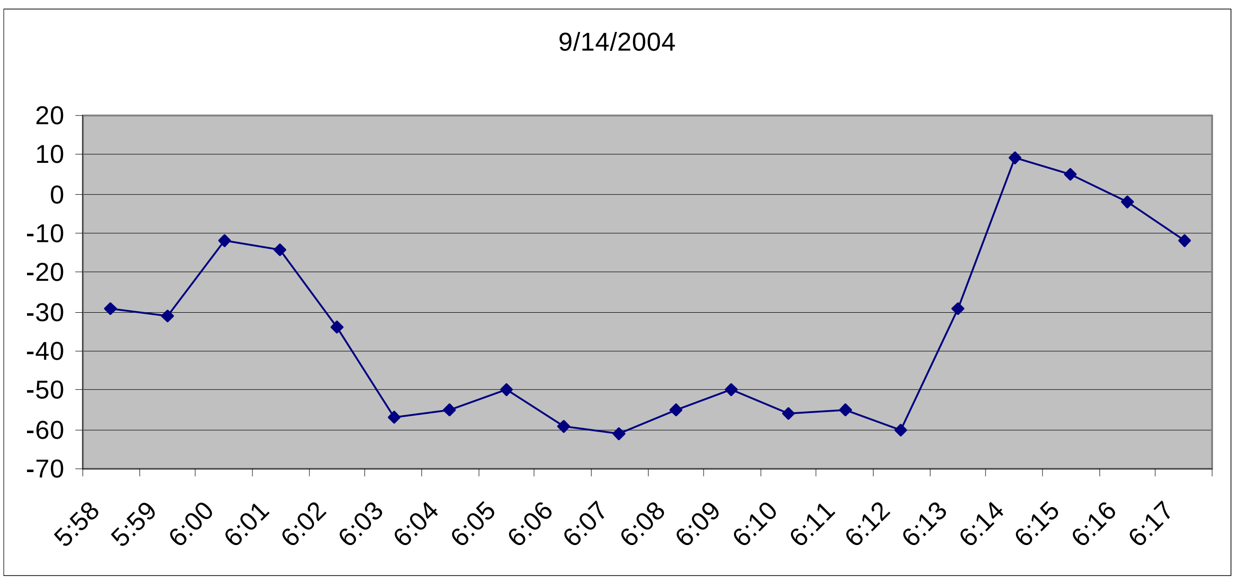

Figure 15. Plot of frequency during a recent frequency excursion lacking a signature of a large contingency.

Another event, graphed in Figure 16 using six-second data, illustrates one of the largest recent frequency excursions. Frequency error went as far as –95 mHz without any apparent signature of a significant generation contingency. As indicated by studies performed of the "hour 22" problem, this is most likely due to poor planning, failing to match schedule ramps during start and end of schedules associated with popular market products, and other aspects of practice [20].

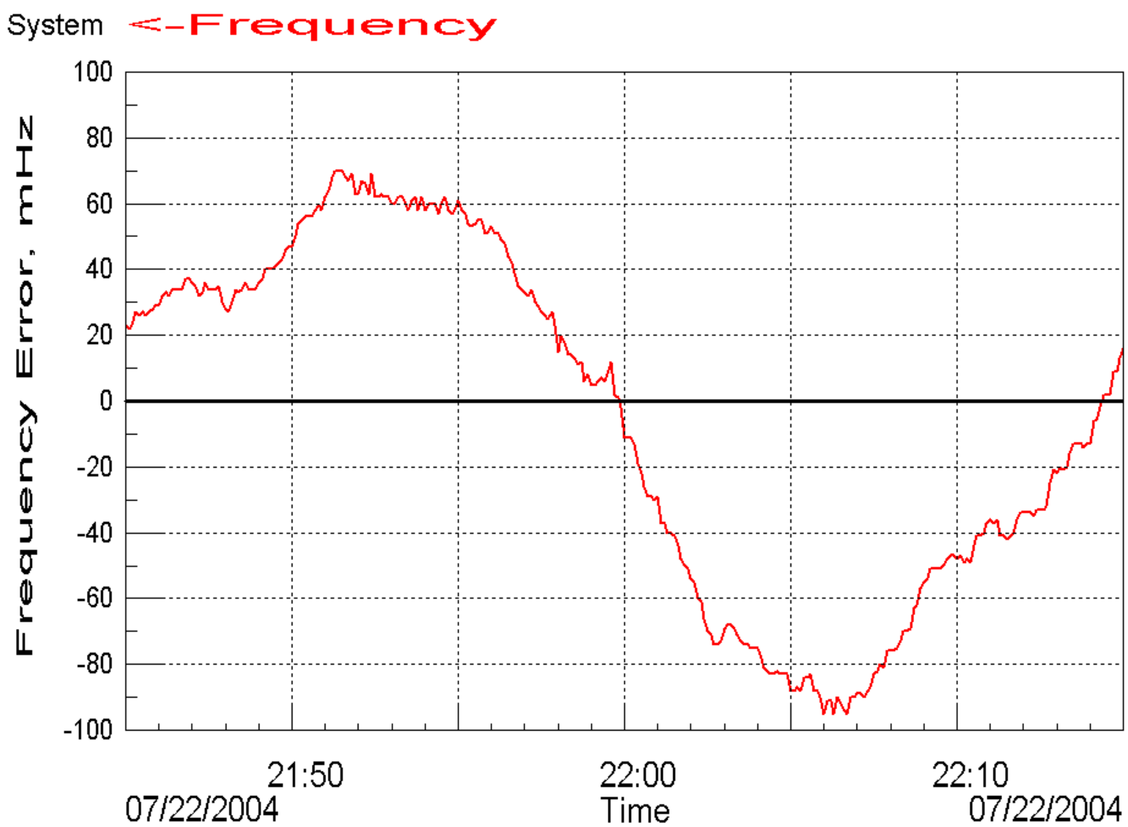

Figure 16. Plot of frequency during a recent frequency excursion lacking a signature of a large contingency.

Extensive PCE experience in enhancing generation control practice to take full advantage of the existing control performance measures indicates that current practice is mainly constrained by CPS2 in the Eastern Interconnection and WECC. Therefore, PCE is certain that should the BAs take advantage of the latitude permitted by the Standard, generation control practice will loosen further. It is impossible to precisely predict BA behavior once the Standard is implemented, as it will depend on the magnitude of the compliance incentives and rapidity of implementation of new methods of control. However, PCE experience with optimizing generation control software indicates that BAs wishing to take maximum advantage of the new Standard will be able to relax their control considerably. Therefore, frequency error at times may substantially, more often than under current practice and with larger magnitude, depart from schedule. The larger the magnitude of such events is and the more frequently they happen, the more significant the risk of frequency reaching FRL can become. At the same time, the risk of wandering outside the targeted Interconnection frequency profile and/or the rate of tripping non-firm load with UFLS relays activated at frequencies above FRL_{low} increases substantially as a result of such behavior.

2. Setting Frequency Limits Based on Experienced/Targeted CPM-1 Performance

The Standard, through the method of calculating FAL it designates, requires that FAL_{low} be selected in such a way that UFLS relays will not be triggered more than once every 10 years even if frequency remains at FAL_{low} for the entire 10 years during non-contingency operation. PCE is aware that FAL_{low}, and possibly FTL_{low}, can be loosened considerably by removing that implicit assumption. This can also be done for FAL_{high} and FTL_{high}. Using a more realistic distribution than the Dirac's delta function assumed by the Standard for FAL_{high} and a different one for FAL_{low} would lead to a less conservative setting of both FAL values. The setting so derived for FAL_{high} and FAL_{low} would, however, be more statistically in line with their proposed use -- the high and low frequency limits during non-contingency operation.

In order to follow this approach, we would have to assume some future distribution of non-contingency frequency errors. In doing so, the following concerns would arise:

- Even if the Interconnection is compliant with CPM-1, we do not know how to predict exactly how far from normal the distribution of frequency in the Interconnection will become once CPS2 is gone in the Eastern and WECC Interconnections, which contain multiple BAs. Even in Howard Illian's ERCOT report [15], which provided valuable insight into analysis of frequency distributions, the final distribution of "normal errors" was not exactly a normal distribution. It is difficult to estimate quantitatively how much difference between the two distributions should be expected over a given time period in a given Interconnection and what impact changes in standards and ACE/frequency control practice would have on that difference.
- The distribution of "disturbance" or frequency error during contingency operation is also not likely to remain the same. Previous research has isolated such data by starting at a large frequency change and stopping when frequency returned to or crossed zero. DCS and CPS2 will be removed, both of which have a significant impact in inducing a fast reduction of ACE, and therefore frequency, following generation contingencies. This is likely to result in a reduced recovery rate, measured as described in Appendix D. With an FTL_{low} as low as 59.950 Hz and the T_{vfl} set to 30 minutes for the Eastern Interconnection, the Standard is likely to have the impacts of increasing the amount of time this Interconnection spends in a 'disturbance' condition and further raising the high-risk tails of the frequency distribution.
- As this report discusses, it is not feasible to confidently estimate the risk inherent in operation with only CPM-1 and the requirement on BAs to return within BAAL within 30 minutes. Many NERC BAs easily have the generation rate to bring ACE to a level above $BAAL_{low}$, after ACE is found to be much below it, within a period much shorter than 30 minutes. Under the Standard, BAs can take advantage of this capability by delaying response to an ACE that is below $BAAL_{low}$ and, hence, avoid unit maneuvering in cases where ACE returns to above $BAAL_{low}$ due to expected favorable changes in obligation. Such action by individual large BAs could cause the frequency to move well beyond FAL_{low}. Alternatively, a combination of smaller BAs, driven by market or grid events, can take actions that have the same effect (this issue with the current measures is described in more detail in section X.2). BAs may be able to do this several times a year while remaining CPM-1 compliant. This might cause the Interconnections to experience more frequent occurrences of large frequency errors than

predicted by the normal distribution of one-minute average frequency error with the targeted RMS.

Despite this, it is possible to assume a very conservative non-contingency frequency distribution, which should compensate fully for the asymmetry and heavy tails of the possible future frequency distribution, and account for any likely changes in generation control practice. The value of FAL calculated based on this assumption could be somewhat farther from 60 Hz than that calculated using the current procedure.

However, PCE believes that, given the uncertainties stemming from the measures in the Standard, it is impossible to produce an accurate estimate of the risk inherent in the Standard. As a result, it is important to conservatively estimate the factors used for setting FTL to help to limit the overall risk of reaching FRL to targeted bounds.

In addition, it is vital to consider the importance of maintaining the targeted Interconnection frequency profile. Since facilities and related protection systems in the NERC Interconnections have been created to support the slowly evolving operation of the North American power systems, it is critical that the new standard ensure that the characteristics of operation do not change too rapidly. As an example, operating under this Standard should not significantly increase the rate at which some UFLS schemes shed interruptible load.

To ensure that the characteristics of operation do not change significantly, the SAR for the Standard requires that Interconnection frequency performance be kept within targeted bounds. In the Standard, the annual RMS of frequency error one-minute averages measures the condition of the frequency profile of the Interconnection. In making the conclusions in this report, PCE has assumed, based on information provided by BRD SDT, that the targeted annual RMS for each Interconnection will remain about the same as its current ε_1 value. Large departure from the current frequency profile, whether it is due to non-compliance of BAs with CPM-1 or increasing the current ε_1 targets, would impact interconnected operation. Quantifying the impacts of such a departure from the current profile is a subject of future research.

In the absence of CPS2 and DCS, it may be necessary to identify the under-performance in real-time and alleviate problems to help realize the targeted annual RMS of frequency error one-minute averages. Thus, it is important that the real-time measures, such as FTL and BAAL, help the RCs and BAs detect and arrest large frequency excursion before they have a chance to threaten the performance of the Interconnection. It is generally not expected that frequency should be beyond the range of 3 to 4 times ε_1 more than a few hours per year in a safely operating CPM-1 compliant Interconnection. Setting FTL_{low} to a value in that range should neither impose unwarranted risk nor noticeably hinder the proper operation of Interconnection participants.

The settings selected for FTL_{low} and FTL_{high} for the Eastern Interconnection in Phase II of the Field Test for this Standard are within these bounds. Such frequency limits should be tight enough to maintain reliability above the desired threshold, but should not require too much unnecessary control actions from RCs and BAs. PCE recommends that frequency limits with values close to these be applied when the Standard becomes fully implemented. Similar procedures should also be applied to select the FTL values for the other NERC Interconnections.

Appendix A. Preparation of Data Obtained from NERC GADS

1. Summary

This Appendix describes how PCE derived the interconnection generation contingency model for use in deriving expected occurrences of various MW deficiencies. The parameters for this model are derived from real historical generation data of immediate forced outages provided by Michael Curley of NERC GADS and obtained from the GADS database.

The process of calculating model parameters involves the following steps:

- Obtaining and organizing input data
- Separating unit and plant trips
- Obtaining trip rates for various sets of units and power plants
- Breaking down the current generation system into sets of similar generating units and power plants based on capacity and type (hydro, fossil, etc.)
- Calculating trip rates for the different sets of units and power plants in the current generation system

2. Obtaining and Organizing Input Data

The following information was available about generating units in the area under NERC supervision:

K	The total number of units in the interconnection.
Cap_k	The capacity of each unit *k*, to the nearest MW.
$Type_k$	The type of each unit *k* (hydro, fossil, etc.)
$Svchrs_{k,L}$	The number of service hours of each unit *k* over time span *L*.
$NOF_{k,L}$	Net Output Factor of each unit *k*, which provides the average actual generation of unit *k* over time span *L* as a percentage of capacity.

Also, GADS provided the time of every reported immediate forced outage, or trip, of those units during the past 10 years.

3. Separating Unit and Power Plant Trips

PCE counted the number of trips for each unit. PCE also defined a power plant trip as an event in which more than one unit from one power plant trips within a short time interval (5 minutes was used for the purposes of this study). The following variables were then calculated for units:

$Trips_{k,\,L}$ The number of trips of unit k over time span L.

$Trips_{k,\,L}$ is computed by counting all trips of unit k over time span L, except those trips of unit k that were part of a trip of a power plant containing unit k.

$Gen_{k,\,L}$ The expected generation of unit k at time of trip during time span L, rounded to the nearest integer MW.

$$Gen_{k,\,L} = NOF_{k,\,L} \times Cap_k$$

The following variables were then gathered or computed for power plants:

${}^{P}K$ The total number of power plants in the interconnection.

${}^{P}Cap_k$ The capacity of plant k, to the nearest MW

${}^{P}Cap_k$ was calculated as the sum of Cap_i of the units in that power plant.

${}^{P}Type_k$ The predominant unit type in power plant k (hydro, fossil, etc.)

${}^{P}Trips_{k,\,L}$ The number of trips of power plant k over time span L.

${}^{P}Trips_{k,\,L}$ was obtained by counting all power plants trips as defined above over a time span L.

${}^{P}Svchrs_{k,\,L}$ The number of service hours of power plant k over time span L.

${}^{P}Svchrs_{k,\,L}$ was calculated as the average of the $Svchrs_{i,\,L}$ of the units in that power plant.

${}^{P}Gen_{k,\,L}$ The expected generation of power plant k at time of trip during time span L, rounded to the nearest integer MW.

${}^{P}Gen_{k,\,L}$ was calculated as the sum of the $Gen_{i,\,L}$ of the units in that power plant.

4. Calculating Trip Rates for Various Sets of Units and Power Plants

For the purpose of smoothing the model in order to reduce the computation time to a reasonable amount, PCE separated all units in the available data into several sets. The expected trip rates were assumed to be equal for all units inside that set. The sets were identified by a capacity integer index *c* and type *t*. Each set, designated with (*c*, *t*) contains all units of type *t* with capacity between $(c-0.5)*R_1$ and $(c+0.5)*R_1$, where R_1 was a constant selected to be the set capacity range. For this study PCE used R_1 of 100 MW.

PCE then calculated the total unit-years of service provided by each such set during the past 10 years of operation in the entire NERC system, $M_{t,c}$, and the average number of trips per unit-year of operation for units in that set, $W_{t,c}$. The value of *L* in the following calculations is set to 10 years.

$$M_{t,c} = \sum_{k=1}^{K} \begin{cases} \dfrac{Svchrs_{k,10yrs}}{8760\, hrs/yr} & c+0.5 < Cap_k/R_1 \le c-0.5 \;\; and \;\; Type_k = t \\ 0 & otherwise \end{cases}$$

$$W_{t,c} = \begin{cases} \dfrac{\sum_{k=1}^{K} \begin{cases} Trips_{k,10yrs} & c+0.5 < Cap_k/R_1 \le c-0.5 \;\; and \;\; Type_k = t \\ 0 & otherwise \end{cases}}{M_{t,c}} & M_{t,c} > 0 \\ 0 & otherwise \end{cases}$$

Similarly, power plants are divided into sets, using R_2 as a constant power plant set capacity range. For this study PCE used R_2 of 500 MW. PCE then calculated the total plant-years of service provided by each such set of plants during the past 10 years of operation in the entire NERC system, ${}^{P}M_{t,c}$, and the average number of trips per plant-year of operation for power plants in that set, ${}^{P}W_{t,c}$. The value of *L* in the following calculations is set to 10 years.

$${}^{P}M_{t,c} = \sum_{k=1}^{{}^{P}K} \begin{cases} \dfrac{{}^{P}Svchrs_{k,10yrs}}{8760\, hrs/yr} & c+0.5 < {}^{P}Cap_k/R_2 \le c-0.5 \;\; and \;\; {}^{P}Type_k = t \\ 0 & otherwise \end{cases}$$

$${}^{P}W_{t,c} = \begin{cases} \dfrac{\sum_{k=1}^{{}^{P}K} \begin{cases} {}^{P}Trips_{k,10yrs} & c+0.5 < {}^{P}Cap_k/R_2 \le c-0.5 \;\; and \;\; {}^{P}Type_k = t \\ 0 & otherwise \end{cases}}{M_{t,c}} & M_{t,c} > 0 \\ 0 & otherwise \end{cases}$$

5. Calculating Generation Contingency Model Parameters

Next, PCE found the total unit-years in service, X_g, and an average trip rate per unit-year, U_g, for units with an expected generation of g, where g is an integer that represents a MW value. In these calculations, PCE used only the most recent data available at the time of analysis (specifically the complete set of 2003 data), to produce a more accurate representation of the actual configuration of the units currently on the interconnection. As a result, L in these calculations is set to 1 year.

$$X_g = \sum_{k=1}^{K} \begin{cases} \dfrac{Svchrs_{k,1yr}}{8760\ hrs/yr} & Gen_{k,1yr} = g \\ 0 & otherwise \end{cases}$$

$$U_g = \sum_{k=1}^{K} \begin{cases} W_{Type_k, \lfloor Cap_k/R_1 + 0.5 \rfloor} X_g & Gen_{k,1yr} = g \\ 0 & \text{otherwise} \end{cases}$$

Separately, PCE found the total plant-years in service, ${}^PX_g$, and an average trip rate per plant-year, ${}^PU_g$, for plants with an expected generation of g.

$${}^PX_g = \sum_{k=1}^{{}^PK} \begin{cases} \dfrac{{}^PSvchrs_{k,1yr}}{8760\ hrs/yr} & {}^PGen_{k,1yr} = \mathrm{g} \\ 0 & otherwise \end{cases}$$

$${}^PU_g = \sum_{k=1}^{{}^PK} \begin{cases} {}^PW_{{}^PType_k, \lfloor {}^PCap_k/R_2 + 0.5 \rfloor} {}^PX_g & {}^PGen_{k,1yr} = g \\ 0 & \text{otherwise} \end{cases}$$

Next, units are sorted into I_u sets, based on their expected average generating level, rounded to R_3 MW. For this study R_3 was set to 100 MW. Each such set has an associated index i, expected generation at time of trip, G_i, total unit-years in service, N_i, and trip rate per unit-year, E_i. Min_i defines the minimum average generating level for each set i, and Min_{i+1} defines the maximum. For each set i, these were computed as follows:

$$1 \le i \le I_u$$

$$Min_i = (i - 0.5) \times R_3$$

$$Min_{I_u+1} = \infty$$

$$G_i = i * R_3$$

$$N_i = \sum_{g=Min_i}^{Min_{i+1}-1} X_g$$

$$E_i = \frac{\sum_{g=Min_i}^{Min_{i+1}-1} U_g}{N_i}$$

Power plants were also sorted into J_p sets, based on their expected average generating level, rounded to R_3 MW. Their associated statistics were then appended to those defined above for the units. For each power plant *j*, they were computed as follows:

$$1 \le j \le J_p$$

$$^{P}Min_j = (j - 0.5) \times R_3$$

$$^{P}Min_{J_p+1} = \infty$$

$$G_{I+j} = j * R_3$$

$$N_{I+j} = \sum_{g={}^{P}Min_j}^{{}^{P}Min_{j+1}-1} {}^{P}X_g$$

$$E_{I+j} = \frac{\sum_{g={}^{P}Min_j}^{{}^{P}Min_{j+1}-1} {}^{P}U_g}{N_{I+j}}$$

In the final step, the final data collection of sets is created by combining the I_u sets of units and J_p sets of plants. The input to the method described in Appendix B is a collection of *I* sets of units or plants, where $I = I_u + J_p$.

Appendix B. Process for Determining the Minimum Safe Megawatt Deadband

1. Introduction

This Appendix describes a process for determining the level of MW deficiency due to generation contingencies that is not expected to occur more than once per 10 years based on available generation contingency data. The process presented here at this time takes into account only immediate forced outages of generating units or entire power plants and ignores potential loss of power delivered through DC/AC converters. Data on generation contingencies necessary to follow this process was produced from information retrieved from the NERC GADS database and processed as described in Appendix A.

This process takes into account probabilities of events involving trips of single as well as multiple unit or power plants. It uses a linear secondary response model to estimate interconnection recovery between generation trips separated in time.

In order to determine the expected number of times a given MW deficiency is likely to occur in a 10-year period, we assume that the 10-year period is a series of T-length time intervals. We consider each such time interval to be a binomial trial, where success is defined by reaching the given deficiency level. The distribution of the number of times a success occurs in a 10-year period can be approximated by a binomial distribution, with an expected value of $P*10yrs/T$, where P is the probability of success in a T-length time interval and $10yrs/T$ is the number of trials. The following sections present a process for estimating P for a given interconnection and a given T.

2. Definitions

For ease of study, the following provides a list of all variables mentioned in this Appendix with their definition:

Set i: a set of units or plants that have similar average generation while synchronized to the grid. Set 0 refers to a special set that is used in our calculations to express the probability of not having a trip of a unit or plant in any set and an expected tripped generation level of 0 MW.

I: total number of sets of units and power plants.

G_i: the expected generation of any unit or power plant in set i at time of potential trip.

n_i: a variable used in the process to indicate the number of units or power plants in set i available to trip in the interconnection, given the outages already assumed in the ancestral steps.

N_i: expected number of units and power plants in set i synchronized at any given time. Equivalent to total unit-years of service for set i per year (calculated in Appendix A).

E_i: expected number of trips in a year for any individual unit or power plant in set i.

T: a time interval, in seconds, that is small enough to make the likelihood of having two independent contingencies within it negligible. A trip of a multi-unit plant is considered for this purpose to be a single independent contingency.

R: secondary response recovery rate of the interconnection, in MW per *T* interval.

D: in MW, indicates an effective MW deficiency, the rate of occurrence of which is sought.

P: the probability that, in a given interval of size *T*, the level of MW deficiency will reach magnitude *D*.

d: in MW, indicates the effective MW deficiency in the interconnection at some given time. It must become greater than *D* for a successful trial.

d_{min} in MW, used in the process to represent a minimum condition that a certain value of *d* must fulfill.

d_{max} in MW, used in the process to represent a maximum condition that a certain value of *d* must fulfill.

z: the amount of error in the calculation of *P*. Given a maximum and a minimum estimate of *P*, the difference between the two.

Z: a value of *z* that we consider necessary to make the associated estimate of *P* acceptably accurate.

T_y: number of seconds in one 365-day year.

3. Assumptions and Approximations

1) In determining the probability of the interconnection facing a MW deficiency equal to or greater than *D* in a *T*-length time interval, if the MW deficiency in the interconnection reaches *D*, all other such instances before the value of *d* returns to 0 belong to the same successful outcome. We prevent these instances from contributing to probability of success, by not counting them as separate successful outcomes. As a result, when determining *P* for an interval, we exclude from consideration all cases where $d > D$ in chronologically earlier intervals.

2) We assume that if a power plant trips, the impact of the loss of the units inside that plant on probability of subsequent unit trips is negligible. In other words, though the probabilities we calculate account for the fact that the plant cannot trip again, they do not account for the fact that the individual units within the power plant cannot. The impact of this simplification of the actual probability is negligible, given that the number of units in the Eastern Interconnection is around 2,600 according to GADS data. However, the reduction of the total number of permutations, and hence computation time, resulting from making this assumption is significant.

3) We assume that secondary response of the interconnection will not reduce the MW deficiency of the interconnection below zero, and, therefore, the value of *d* must always be zero or positive.

4) It is assumed that a particular unit is not likely to trip more than once during the total time span considered by this process to estimate the impact of multiple contingencies. Thus, when considering possible combinations of contingencies, the number of trips involving the i^{th} set of units can never exceed the original N_i.

5) The generation of any given unit in set i at the time of a trip is approximated to be at a level G_i, which is its average expected generation calculated from GADS information.

6) As noted in the definition of T, we choose a value such that the probability of two units or plants tripping in the same interval is minimal. Therefore, we can make the assumption that two units or plants will not trip in the same T-length interval, removing many permutations that add very little to probability, but which enormously increase the computation time.

7) Unit trip events, if any, are assumed to happen at the very end of the interval.

4. Initial Functions

We need to derive several functions in order to explain the process.

Since it should be physically impossible for a single unit to trip twice in time T, the expected number of trips per T-length interval for any unit/plant in set i, $E_{i,T}$, is calculated as:

$$E_{i,T} = \frac{TE_i}{T_y} \qquad \text{(B-1)}$$

We need to estimate the probability $P_{i,T}$ that one unit in set i, where $i > 0$, will trip in a given T-length time interval. As we have assumed that we set T small enough to ensure that the probability of having more than one unit trip in a given time interval of length T is negligible, it can be approximated by:

$$P_{i,T} = n_i \times E_{i,T} \qquad \text{(B-2)}$$

The probability that no units will trip in a given interval of length T is the product of the probabilities of not tripping, (1 - $E_{i,T}$), for each of the N_i synchronized units in each of the I sets:

$$P_{0,T} = \prod_{i=1}^{I} \left(\left(1 - E_{i,T}\right)^{N_i} \right) \qquad \text{(B-3)}$$

Since each of the NERC interconnections has such a significant number of units that removing one or several units is not likely to change $P_{0,T}$ significantly, in each step of the process we will calculate this value by using all of the units in the interconnection without considering that some units may have already tripped. While this may have an impact on the results in the example scenarios below where only a small number of units are considered to be available, it does not have a noticeable impact on calculations performed for actual NERC interconnections.

5. Determining *P*

This section, using several examples, gradually develops the basis for a process of determining *P*, i.e. the probability of the interconnection facing a MW deficiency of magnitude *D* in a *T*-length time interval. It is not practically feasible to exactly determine this probability for a typical data set, such as the data we have used for 2,600 units in the Eastern Interconnection. Instead, this process determines a maximum and minimum between which the probability of this outcome should fall, and tries to reduce the difference between the two, referred to as "error" or *z*, below some threshold of acceptability, referred to as *Z*.

In general, the process makes use of a tree structure for representing all known data regarding the system so far. For each step, the process determines whether *z* is below *Z*; if not, it expands the tree and performs additional calculations to further reduce this difference. Otherwise, it reports the final results for the maximum and minimum *P*, which we can then directly use to estimate the expected number of successes in 10 years.

We are trying to find the probability that, for a certain interval, *d* will exceed *D*. We will refer to this certain interval as interval 0 for the remainder of this section. We will also refer to other intervals in terms of their chronological relationship to interval 0. For example, the interval immediately preceding and ending at the beginning of interval 0 would be interval 1. The interval that precedes interval 1 would be interval 2. Interval *j* begins $j \times T$ seconds before and ends $(j-1) \times T$ before the beginning of interval 0. To emphasize, higher numbers actually represent earlier intervals, not later intervals.

Overview of Notation

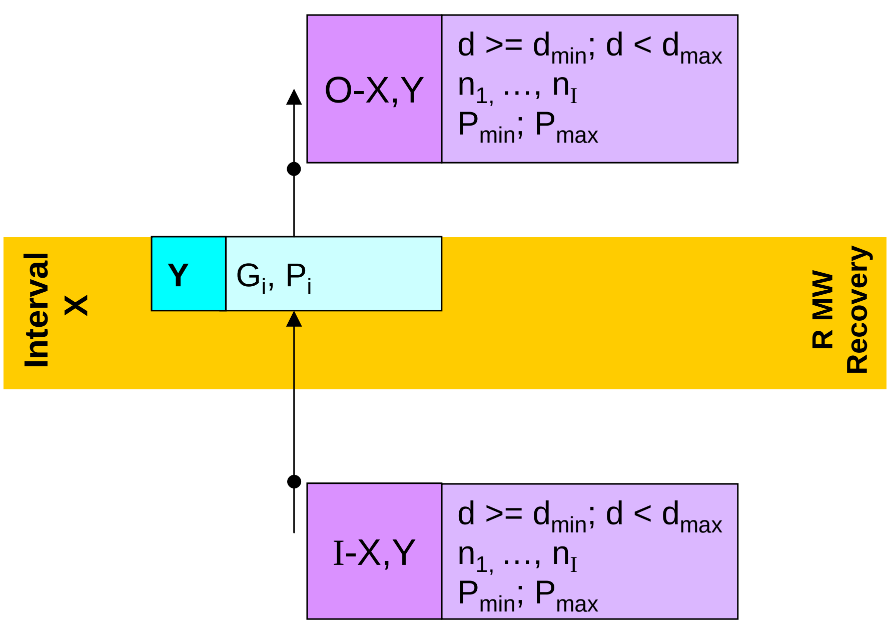

Figure 17. Overview of Notation.

In general, our process utilizes a tree consisting of branching chains of events. Each "element" in the tree, as shown in Figure 17, deals with a certain event *Y* occurring in a certain interval *X*.

While different elements in the same interval *X*, indicated with distinct values of *Y*, can refer to the same event, they will differ as to their ancestors. Thus, any element or series of events in the solution tree can be referenced by a unique combination of "*X*, *Y*". The maximum value of *Y* for a certain interval tends to have an exponential relationship with the value of *X*.

In any interval *X*, we assume that the interconnection decreases the power deficiency by *R* MW due to secondary frequency response during the interval.

Event *Y* either represents the trip of one unit or plant in some set *i*, or no trip of any unit. The increase in deficiency is either G_i, or 0 if no unit or plant trips. There is a probability associated with each event as well. The probability that a unit or plant of a certain set will trip is defined in Equation B-2. The probability that no units or plants will trip is defined in Equation B-3.

At the point indicated by "O-X, Y" ("O" represents output, as the point is immediately after the end of interval *X* and event *Y*) d_{min} and d_{max} represent conditions that *d* must meet immediately after interval *X* so that there will ultimately be a deficiency of at least size *D* in interval 0. The values $n_1, \ldots, n_I$ are the number of units in the *I* sets of units or plants whose trips have not been considered in the elements of the tree ancestral to this element. The values P_{min} and P_{max} represent the minimum and maximum probability that $d_{min} <= d < d_{max}$, as specified above.

At the point indicated by "I-X, Y" ("I" represents input, as the point is immediately before the start of interval *X*, with event *Y* occurring at the end of the interval), d_{min} and d_{max} represent conditions that *d* must meet immediately before interval *X* so that, if the event occurs, the conditions in "O-X, Y" are fulfilled. In general, d_{min} of "I-X, Y" is equal to d_{min} of "O-X, Y" minus the generation change in interval *X*, both from event *Y* and the recovery of *R* MW, but d_{min} cannot be lower than 0, as per Assumption 3. Similarly, d_{max} of "I-X, Y" is equal to d_{max} of "O-X, Y" minus the generation change in interval *X*, both from event *Y* and the recovery of *R* MW, but d_{max} cannot be higher than *D*, as per Assumption 1.

$$d_{\max,child} = \min(d_{\max,parent} - G_{parent} + R, D) \qquad \text{(B-4)}$$

$$d_{\min,child} = \max(d_{\min,parent} - G_{parent} + R, 0) \qquad \text{(B-5)}$$

The values $n_1, \ldots, n_I$ for point "I-X, Y" are the number of units in each of the *I* sets of units or plants that are available for trip consideration in the preceding elements. If event *Y* is the trip of a unit/plant from set *i*, then n_i in "I-X, Y" is one lower than n_i in "O-X, Y", and $n_1, \ldots n_{i-1}$, as well as $n_{i+1}, \ldots n_I$ are the same as the corresponding values in "O-X, Y". This is because the one unit/plant from this set that tripped in interval *X* could not have tripped earlier. If event *Y* is no trip, then $n_1, \ldots, n_I$ are the same as the corresponding values in "O-X, Y".

P_{min} and P_{max} represent the minimum and maximum probability that $d_{min} <= d < d_{max}$, using the value of *d* at the start of interval *X* and d_{min} and d_{max} as specified in point "I-X, Y".

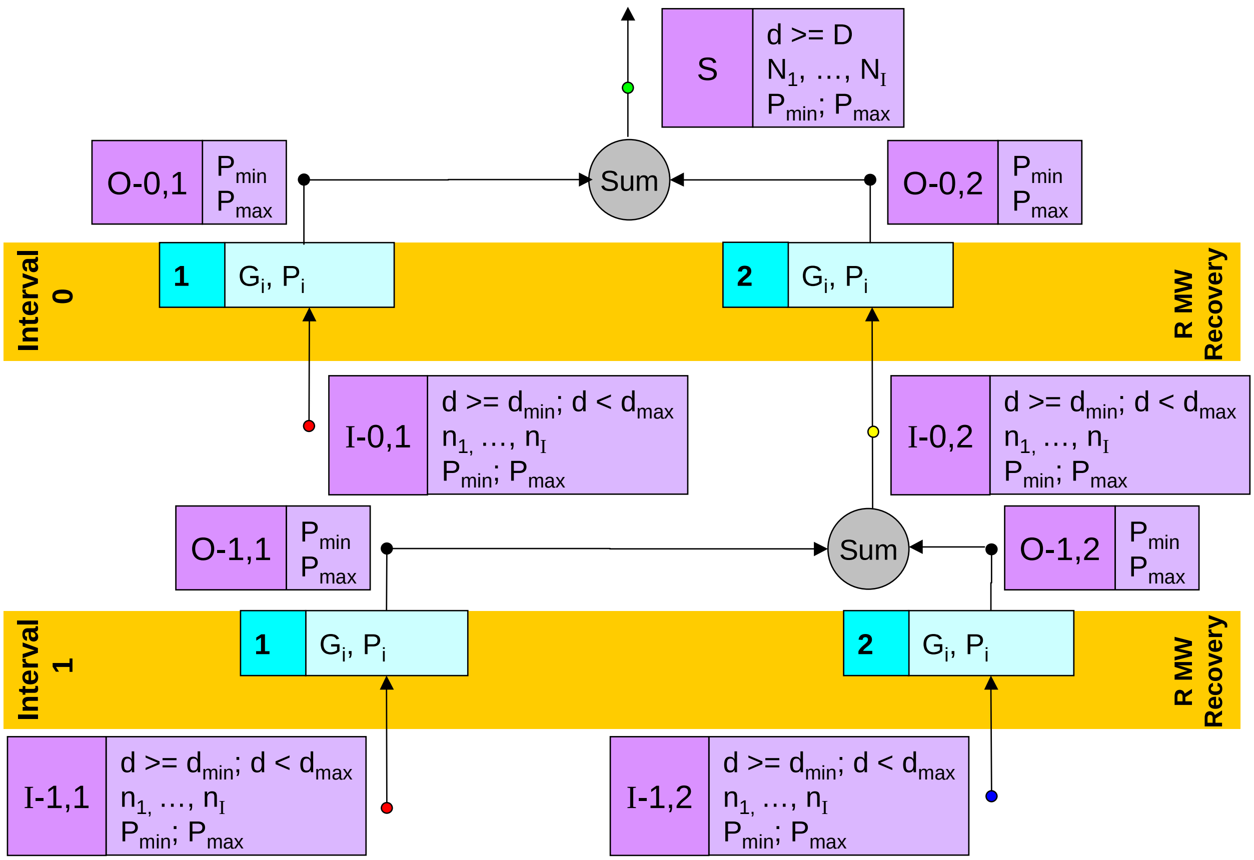

Figure 18. Linking elements of the tree.

Figure 18 shows how these elements link together to form a full tree.

The points that actually link the elements of the tree together are shown in yellow (e.g. "I-0, 2") and black (e.g. "O-1, 1", "O-1, 2"). Each element containing a yellow point can connect to up to $I+1$ other elements containing black points, one associated with a trip of a unit in each of the I sets where a unit is available, and one associated with no trip. The values of d_{min} and d_{max} are the same for a given yellow point and all connected black points; thus to limit redundancy and improve image clarity, only the yellow points show d_{min} and d_{max}. P_{min} and P_{max} of the yellow point are the respective sums of the P_{min} and P_{max} values for each of the connected black points.

We can follow a "path" from the black point of one element to the yellow point of another; and from the black point of that element to the yellow point of another; and so on, until we reach the green point at the top of Figure 18, discussed below. By doing so, we can trace a "chain of events" over several intervals, ending immediately after interval 0. For example, from Figure 18, Event 1 in interval 1 is followed by Event 2 in interval 0.

The red "I-X, Y" points are terminal. These represent a chain of events where the conditions on d will either definitely be met, or cannot be met. If d_{min} is less than R, then P_{min} and P_{max} are equal and are considered to be 1 at "I-X, Y". The reasoning is as follows:

- As per Assumption 3, d must always be greater than 0. Therefore, for any value of d where $d <= R$ at an "I-X, Y" point before the event interval, we can assume that deficiency has decreased to 0 at the time of the trip, which is assumed to occur at the end of the interval.

- The probability that $d < d_{max}$ is very near to 1.

On the other hand, if d_{min} is higher than d_{max}, the conditions are contradictory. The value of d can never be less than d_{max} and greater than d_{min} in such a case, so P_{min} and P_{max} at "I-X, Y" are exactly 0. Either way, there is no need to examine earlier intervals.

Note that any "I-X, Y" points that are shown in blue at the end of each calculation step are elements that can be expanded, but are considered terminal for the purpose of calculating z at the end of each step. In this case, the chain of events can branch, as was the case with the yellow points. However, we have not yet performed the necessary calculations to do so. Instead, an estimate of the minimum and maximum probability is substituted. These points are the source of the error that must be minimized through the process being described in this section.

Finally, note that the topmost point, in green, is identified as "S". This is the solution point. The d_{min} for this point is D. There is no d_{max}. $n_1, \ldots, n_I$ are equivalent to $N_1, \ldots, N_I$. P_{max} and P_{min} represent the total maximum and minimum probability of success, the difference of which is z.

Example 1

Consider an interconnection with $I = 1$, $G_1 = 1{,}000$ MW, $N_1 = 2$, and a secondary response rate of 200 MW/min. Use $T = 30$ s, $E_1 = 2{,}102$, $D = 1{,}400$ MW, and $Z = 1.4\text{e-}4$ (the notation 1.4e-4 indicates a value of 1.4×10^{-4}) to find the minimum and maximum values of P, such that $z < Z$.

First, from Equation B-1, we can determine that $E_{1,30} = 0.002$. Also, we calculate $R = 200MW * 30s / 60s = 100MW$.

Example 1, Step 1

Figure 19 shows our initial knowledge. We have no elements in the tree, only point "S". We understand that, for a successful outcome, our final level of deficiency must exceed 1,400 MW. What are good initial estimates for the minimum and maximum probabilities of a successful outcome, without extensive examination of the possible events that may have occurred in interval 0 or earlier?

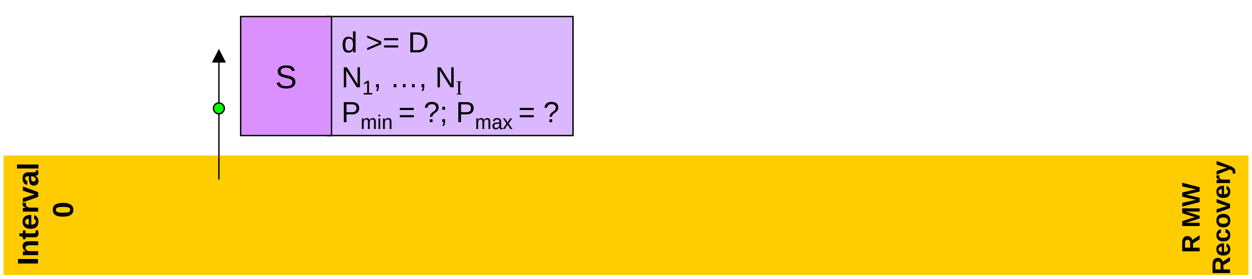

Figure 19. Tree for Example 1, Step 1.

We can immediately set P_{min} to 0 and P_{max} to 1, as these are the logical extremes of probability. However, there is one simple calculation that will remove a great deal of this error. From Assumption 1, we know that we can discard scenarios where $d >= D$, except in the last interval.

We can say with certainty that if $d < D$ at the end of interval 1 and we trip no units in interval 0, then $d < D$ at S. Therefore, we should remove from the maximum probability of success the probability that we trip no units in interval 0, which is approximately 0.996, per Equation B-3. The value of P_{max} at S, therefore, becomes 1- 0.996, or 0.004.

We calculate error from P_{min} and P_{max} at point S. The difference between 0.004 and 0 is 0.004, which is larger than the specified Z.

Example 1, Step 2

There is too much error in the probabilities calculated in Step 1. If we look at all possibilities for trips in the current interval 0 then we can refine our estimates of the minimum and maximum probability values, by expanding the depth and accuracy of our calculations.

To expand the accuracy of our calculation, we must first enumerate the possible events to consider in the current interval. We have assumed that the probability of multiple units tripping in the same interval is negligible. Only two other possibilities exist. One is that one of the 1,000 MW units will trip. The other is that no unit will trip. These possibilities are illustrated in Figure 20.

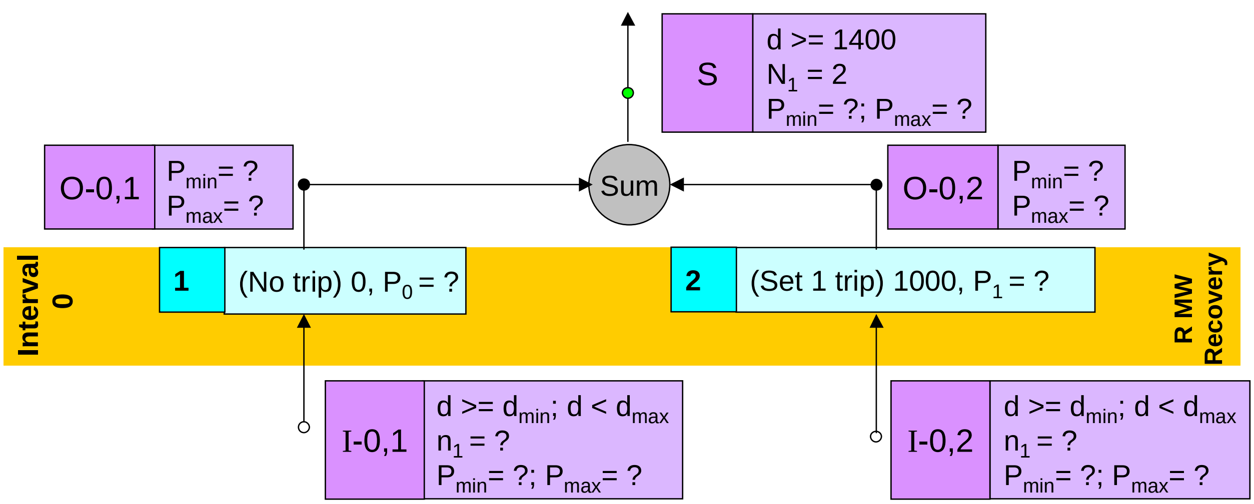

Figure 20. Tree for Example 1, Step 2.

Next, we need to determine how much each possible event contributes to P_{min} and P_{max}. First, let us examine the case where no unit trips in interval 0. From examining Figure 20, we can see that we must determine P_{min} and P_{max} for point "O-0, 1". Doing so will require determining P_0 for the box labeled "1", and d_{min}, d_{max}, n_1, P_{min}, and P_{max} for point "I-0, 1".

A. What is the probability that no unit will trip in interval 0?

   The answer, from Equation B-3, is 0.996.

B. What is d_{min} for point "I-0, 1"?

   From Equation B-5, d_{min} = 1,500 MW.

C. What is d_{max} for point "I-0, 1"?

Because we only want to ensure that the final level of MW deficiency is above some number, there was no d_{max} for point "S". Thus, no condition is propagated to point "I-0, 1". However, d must be less than D. Therefore d_{max} for point "I-0, 1" is 1,400 MW.

D. What number of units in set 1 will be available for consideration in elements derived from "I-0, 1"?

   No unit trips are involved in this event, so n_1 remains at 2.

E. What is P_{min} for point "I-0, 1"?

   The value of d_{min} is higher than the value of d_{max}. These conditions are contradictory, so P is exactly 0. Thus, P_{min} is 0.

F. What is P_{max} for point "I-0, 1"?

   From above, P is exactly 0. Thus, P_{max} is 0.

We now have enough information to estimate P_{min} and P_{max} for point "O-0, 1". As we have determined that there is no chance whatsoever that d in interval 1 can meet the needed conditions, both the minimum and maximum probability that we can meet the conditions for point "O-0, 1" are also 0.

Next, let us determine the contribution of the potential 1,000 MW unit trip to P_{min} and P_{max}.

G. What is the probability that a 1,000 MW unit will trip in interval 0?

   The answer, from Equation B-2, is 0.004.

H. What is d_{min} for point "I-0, 2"?

   From Equation B-5, $d_{min} = 500$ MW.

I. What is d_{max} for point "I-0, 2"?

   Because we only want to ensure that the final level of MW deficiency is above some number, there was no d_{max} for point "S". Thus, no condition is propagated to point "I-0, 2". However, d must be less than D. Therefore d_{max} for point "I-0, 2" is 1,400 MW.

J. What number of units in set 1 will be available for consideration in elements derived from "I-0, 2"?

   One set 1 unit is tripped in this event, so n_1 decreases by 1, to 1, for preceding intervals.

K. What is P_{min} for point "I-0, 2"?

   The values of d_{min} and d_{max}, are not contradictory, nor do they imply guaranteed success. Without further examination of past conditions, we can set P_{min} to 0, as in Step 1.

L. What is P_{max} for point "I-0, 2"?

   As in Step 1, we can immediately rule out some portion of P_{max}. Consider the case where no unit trips in interval 1. Because d must have been less than 1,400 MW at the start of interval 1 (from Assumption 1), and because 100 MW were recovered over interval 1, d could be at most 1,300 MW in interval 0. Likewise, if no units tripped in both interval 1 and interval 2, then d could be at most 1,300 MW in interval 1 and therefore 1,200 MW in interval 0.

How is this relevant? We know that d_{min} is 500 MW. Therefore, a situation that would force d to be less than 500 MW will not contribute to the probability of success at this point. How many consecutive intervals with no trips would it require to result in such a situation? The answer is dependent on D, on the d_{min} for this point, and on the recovery rate, using the formula $\lceil (D - d_{\min})/R \rceil$. We use the ceiling function, because any fraction of an interval implies another full interval is required to force d below d_{min}. Using this formula for D of 1,400 MW, d_{min} of 500 MW, and R of 100 MW gives us 9.

Thus, we calculate P_{max} by subtracting the probability that no unit will trip for 9 consecutive intervals, or 0.996 to the 9th power, from 1. P_{max}, then, is 0.035429. In general, we can always initially estimate P_{max} for point "I-X, Y" as

$$1 - P_0^{\lceil (D - d_{\min})/R \rceil} \qquad \text{(B-6)}$$

using the value of d_{min} at point "I-X, Y".

We now have enough information to estimate P_{min} and P_{max} for point "O-0, 2". P_{min} is determined by multiplying the probability that the event will occur (0.996) by the minimum probability that the additional conditions for "I-0, 2" will be met, which is 0. Thus, P_{min} = 0. P_{max} is determined by multiplying the probability that the event will occur (0.004) by the minimum probability that the additional conditions for "I-0, 2" will be met (0.035429). Thus,
P_{max} = 1.4172e-4.

Having examined each possible event at interval 0, what are more accurate estimates of P_{min} and P_{max} for point "S"? What is the remaining error? Figure 21 illustrates this question.

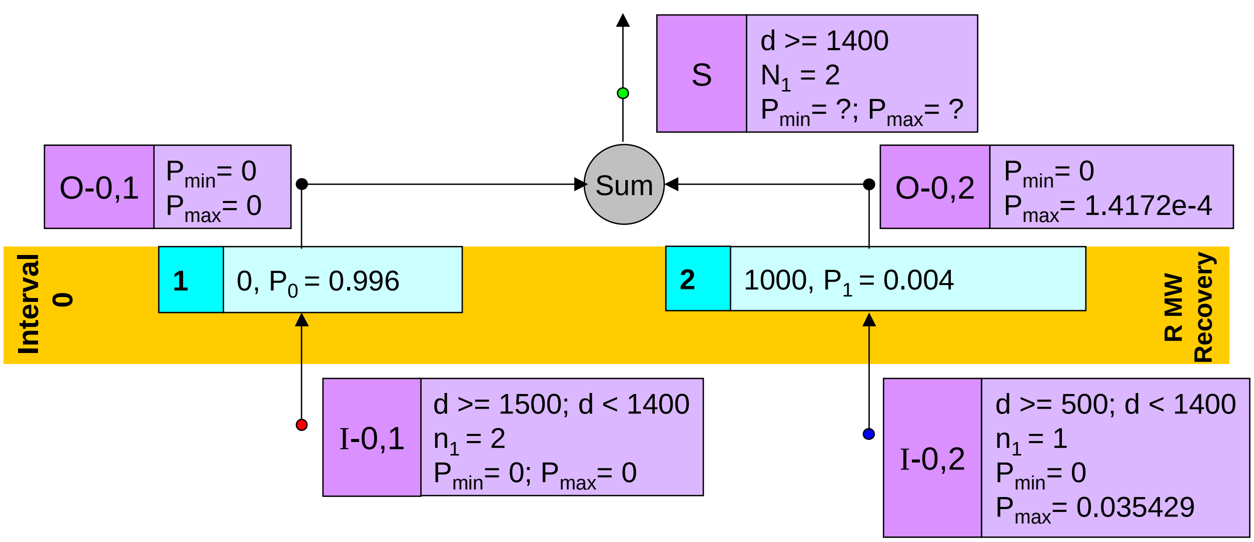

Figure 21. Finding P_{min} and P_{max}.

To find P_{min} for point S, add the individual P_{min} values for "O-0, 1" and "O-0, 2". Thus, P_{min} = 0 + 0 = 0. To find P_{max} for point S, add the individual P_{max} values for "O-0, 1" and "O-0, 2". Thus, P_{max} = 0 + 1.4172e-4 = 1.4172e-4. Finally, $z = P_{min} - P_{max}$, or 1.4172e-4.

Example 1, Step 3

Because 1.4172e-4 is still larger than *Z*, we must perform more calculations and increase our tree of knowledge. Only blue points are candidates for expansion, and the only blue point is “I-0, 2”.

Figure 22 shows the possible events that could occur in interval 1, given the occurrence of event 2 in interval 0.

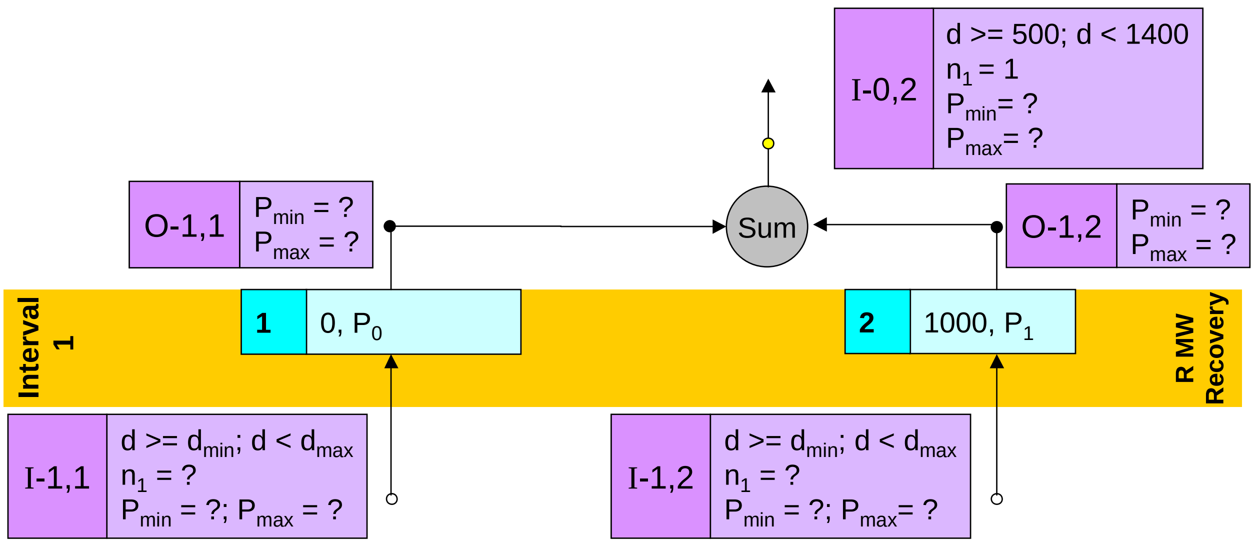

Figure 22. Tree for Example 1, Step 3.

Figure 23, below, shows the correct values in place of each question mark. It also uses these values to update the values of P_{min} and P_{max} for point “I-0, 2”. Note that both P_{min} and P_{max} for point “I-1, 2” are set to 1, because *d* will definitely be greater than the specified d_{min} of 0, and d_{max} plays a negligible role in probability. Refer to previous sections for more information on how these values were calculated.

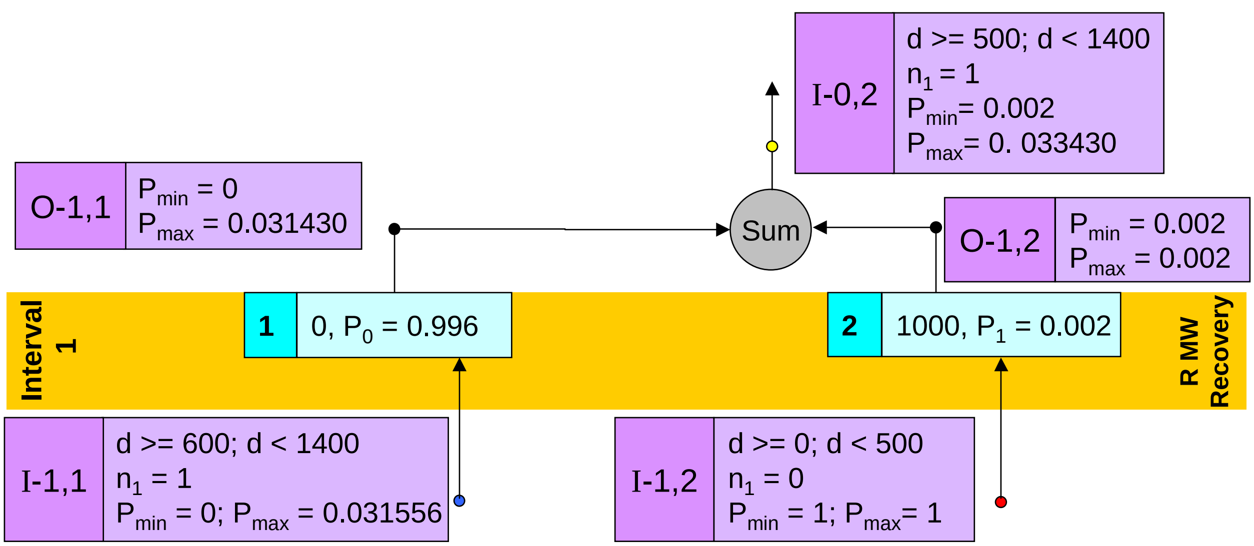

Figure 23. Finding P_{min} and P_{max}.

Now that we have updated P_{min} and P_{max} for point "I-0, 2", we can update point "O-0, 2". In general, we would continue directly up the tree from child element to parent element. Each time, we would do the following:

1. Use the new "O-" point of the child element to recalculate the values in the "I-" point of the parent element.
2. Use the "I-" point of the parent element to recalculate values in the "O-" point of the parent element.
3. Consider the parent element to be the new child element (for the next closest element to S).
4. Consider the next closest element to S to be the new parent element.
5. Repeat the process from step 1 with the new child and parent elements determined in steps 3 and 4.

Finally, we would use the "O-" point of the element in interval 0 to update point "S".

Figure 24, below, shows the updated tree, with new values of P_{min} and P_{max} for point "S".

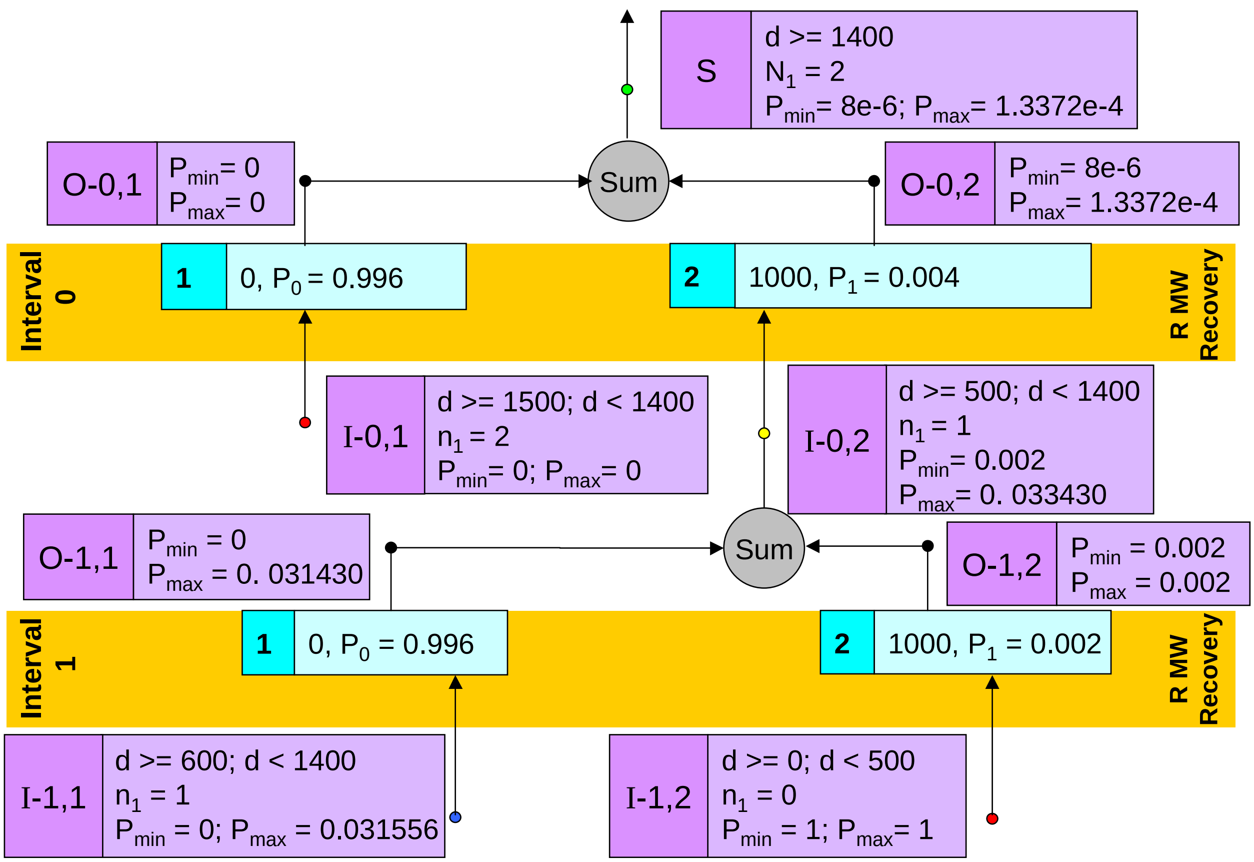

Figure 24. Finding P_{min} and P_{max}.

Thus, we consider the final probability of success to be between 8.0e-6 and 1.3372e-4. Based on the newly calculated values of P_{min} and P_{max} for point "S", $z = P_{max} - P_{min}$ = 1.2600e-4, which is less than Z. We have reached a level of error that we have deemed acceptable for this example.

Since T is 30s in this example, in 10 years there are 10,512,000 trials, so we expect the number of successes in 10 years to range from approximately 84 to 1,406. In general, in utilizing this process to estimate the size of the largest contingency that is expected to occur more than once per 10 years we will set *Z* so as to target a much smaller magnitude of the range in the number of successes in 10 years.

Example 2

This problem features a slightly more complicated interconnection, with three potential sets of units that can trip. *T*, *R*, and *D* remain the same as in Example 1.

Set 1: $G_1 = 500$; $E_{1,30} = 0.01$; $N_1 = 3$

Set 2: $G_2 = 1{,}000$; $E_{2,30} = 0.02$; $N_2 = 2$

Set 3: $G_3 = 1{,}500$; $E_{3,30} = 0.01$; $N_3 = 1$

For the given tree pictured in Figure 25, which elements are available to expand next? Of these, which elements might reduce the error faster?

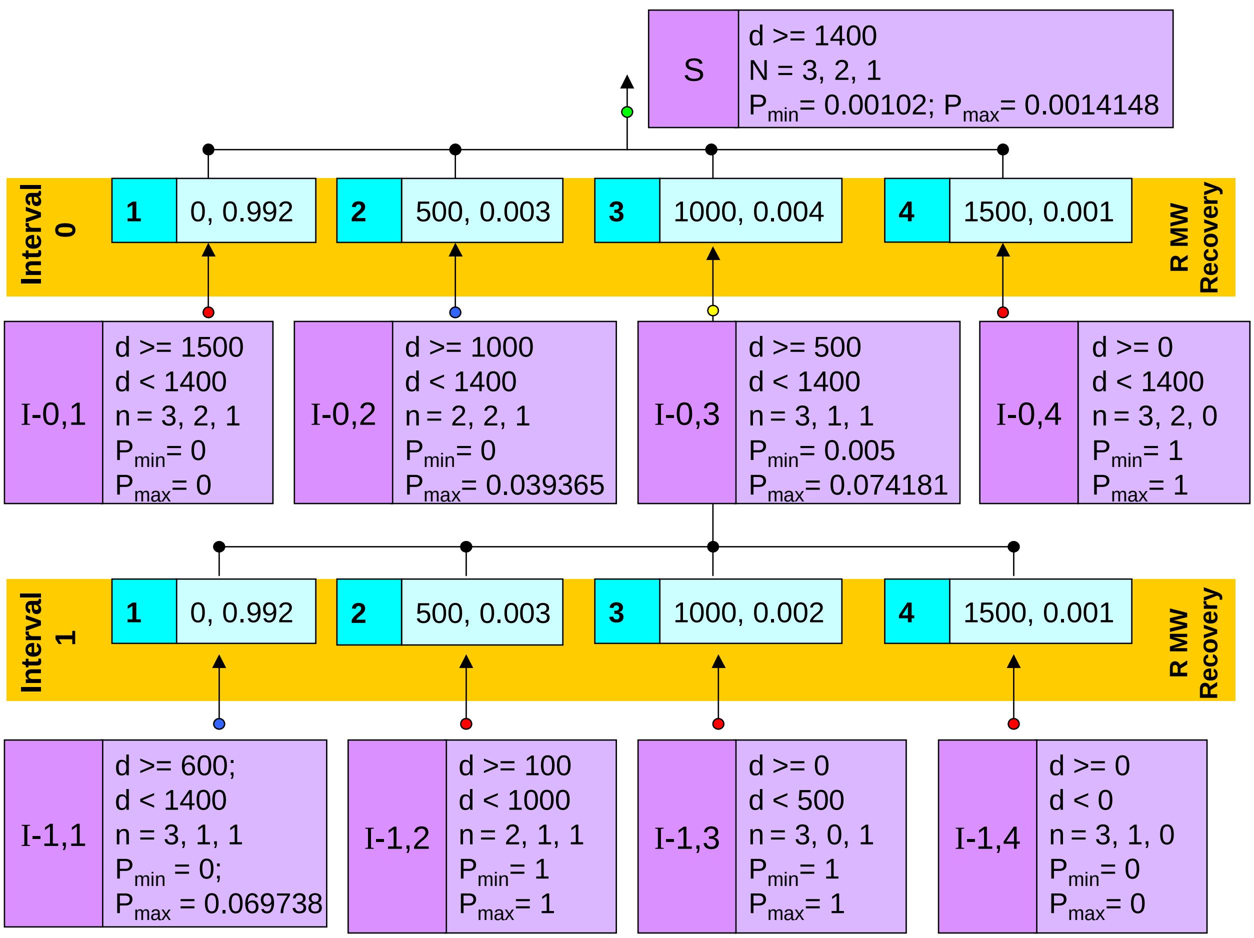

Figure 25. Tree for Example 2.

At the point in calculations shown by Figure 25, there are only two blue points, each contributing some portion of *z*, point “I-0, 2” and “I-1, 1”.

We can use a simple heuristic to decide which of the two elements to expand, in order to reduce error with fewer steps: simply compare the amount contributed to *z* by each element. If we assume that the reduction in total error, or *z*, resultant from expansion of an element has a somewhat proportional relationship with the amount of error contributed by that element, then expanding the element that accounts for the largest portion of the error is likely to remove the largest amount of error.

Figure 26 shows only the portion of Figure 25 that is ancestral to the two elements that we can expand, as well as the elements themselves.

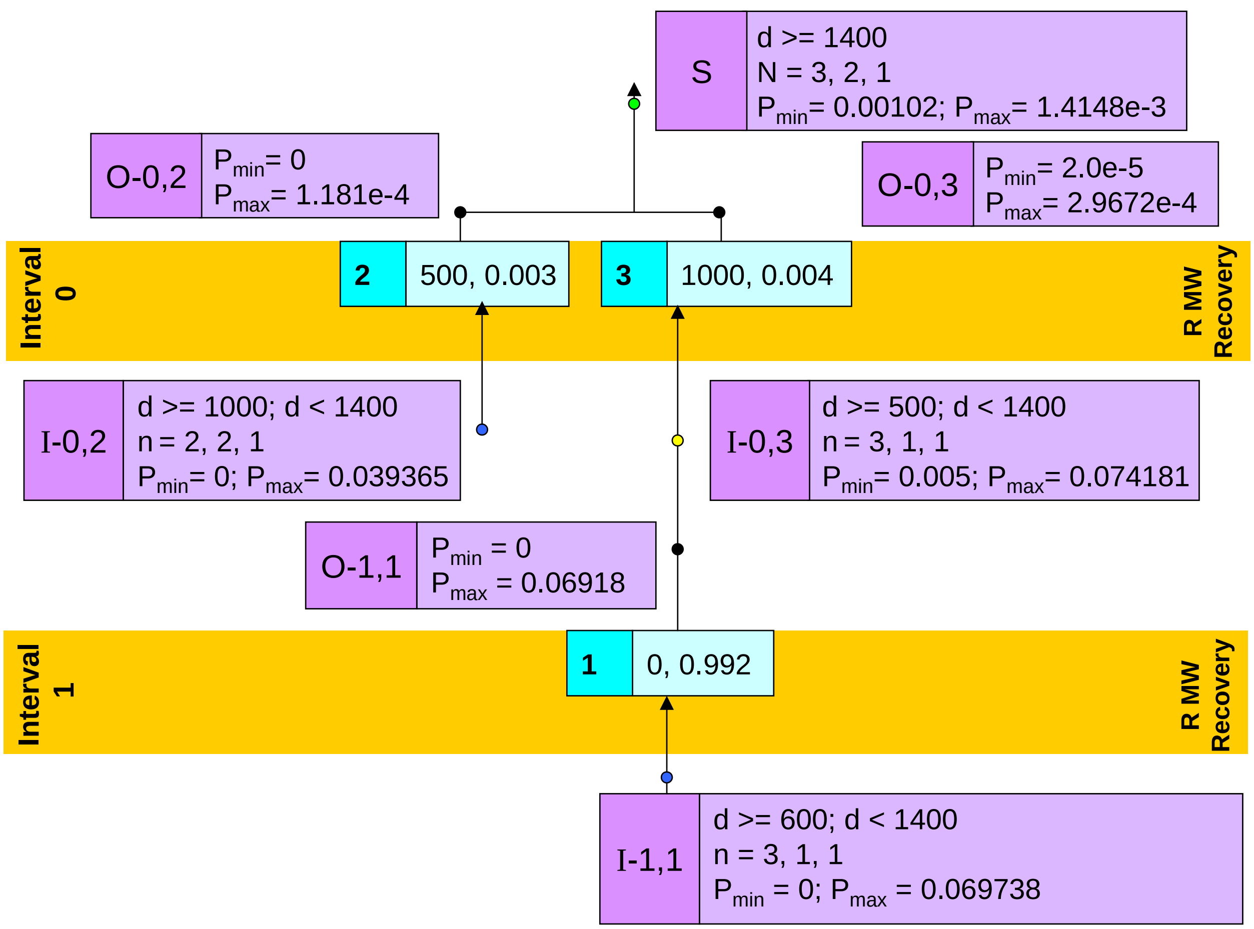

Figure 26. Expanding tree for example 2.

For element “0, 2”, the portion of *z* is the difference between P_{max} and P_{min} for point “O-0, 2”, or 1.1810e-4. For element “1, 1”, however, it is somewhat more complicated. From Figure 26, we can see that the element contributes to a sum probability at point “I-0, 3”, which is then multiplied by an event probability for event “0, 3” to calculate P_{max} and P_{min} for point “O-0, 3”, which contribute directly to *z*. Thus, the portion of *z* derived from “1, 1” is equal to the difference between P_{max} and P_{min} of point “O-1, 1” (0. 06918), multiplied by the probability of event “0, 3” (0.004), or 2.7672e-4.

More generally, the contribution of an element “X, Y” to z is calculated by taking the difference between P_{max} and P_{min} at point “O-X, Y”, then multiplying it by the event probability for each higher connected element.

In this case, element “1, 1” contributes 1.1810e-4 to the error, while element “0, 2” contributes 2.7672e-4 to the error. In our next step, we would expand element “0, 2”.

Conclusion

In summary, our process is an iterative method that continually traverses and expands a knowledge tree. For each step, we perform the following actions:

1. Find the element "X, Y" that makes the greatest contribution to the error. For the first step, all elements will be expanded from point "S", which is considered to be an element for that purpose.
2. Create up to $I+1$ sub-elements in interval $X+1$, branching from element "X, Y", one representing the case where no unit trips and one for each set in which a unit or plant is available to trip. For the first step, substitute interval 0 for interval $X+1$.
3. For each sub-element, referenced by X, Y, thus created, use the values of d_{min}, d_{max}, and n_1, …, n_I from point "O-X, Y" to determine the values of d_{min}, d_{max}, and n_1, …, n_I for the sub-element.
4. For each sub-element, use the conditions to determine P_{min} and P_{max}. If P_{min} is not equal to P_{max}, then the element contributes to z and is a candidate for expansion in future steps.
5. Use the P_{min} and P_{max} for each sub-element to recalculate P_{min} and P_{max} for element "X, Y". Continue to propagate modified values directly up the tree until point "S" is updated.
6. Use P_{min} and P_{max} at point "S" to recalculate z. If $z >= Z$, go to step 1 to expand another element.

Once $z < Z$, we have determined an acceptable range of values for P, which we will use to determine the number of expected successful outcomes in 10 years. The number of successful outcomes for different values of D can then be used to determine the largest level of MW deficiency due to generation contingencies that is expected to occur more than once per 10 years.

Appendix C. Specific Proposed Areas of Potential Improvement in the Standard

1) Clarification of "approved (firm load) Under Frequency Load Shed relay" in the proposed process for setting frequency limits. The Standard should specify who must provide approval and refer to a specific definition of firm load.
2) Clarification of "approved high frequency relay or turbine overspeed setting for the interconnection consistent with the Interconnection's reliability requirements" in the proposed process for setting frequency limits. The Standard should specify who must provide approval, which units' relay setting may be considered (type, minimum size, etc.), and refer to a definition of "Interconnection reliability requirements".
3) Limiting FTL_{low} and FTL_{high} to a magnitude a few times ε_1 away from scheduled frequency for all Interconnections.
4) Setting FTL_{low} some magnitude higher than all frequency-activated UFLS settings (firm and non-firm) in an Interconnection.
5) Changing the label of Requirement **R5** to **R4.8** in BAL-011-1.
6) Modifying BAAL formulation and/or measures to have a closer relationship with NERC's reliability objectives and to distribute control responsibility more fairly.
7) Modifying the name of the different T_v values in the existing measures to reflect their different meanings and ease communication, even if their values are initially selected to be equal to each other. One approach is to use the names T_{vb}, T_{vfl}, T_{vfh}, defined in this report.
8) Specifying a more technically defensible process for calculating T_{vfl} and T_{vfh}.
9) The Standard should be modified to clarify the definition of "single contingency" in developing FTL. For example, it should clarify whether plant trips can be considered a single generation loss contingency.

Appendix D. Process for Determining the Recovery Rate

1. Background

Recovery rate is an estimate of the time it takes for frequency to return to normal following a contingency, relative to the size of the contingency. Recovery rate is a factor in determining the extent to which frequency deviates in follow up to contingencies as a result of other prior contingencies. PCE used this result in the process of determining Minimum Safe Megawatt Band. PCE calculated the frequency recovery rate by identifying generation contingencies based on their signature in the historical frequency trend and dividing the follow-up frequency rise to a normal range by the time needed to realize that rise. PCE then derived the recovery rate in MW/min by multiplying the frequency recovery rate by an estimate of frequency response.

For the sake of time efficiency, the algorithm for calculating recovery rate had two phases. The Parsing phase was more time-consuming and heavily dependent on the format of the raw frequency data. This phase included the performance of the bulk of the processing work that was not likely to be repeated, including the isolation of possible contingencies with very inclusive standards and the creation of uniformly formatted files designed to improve the efficiency of the second phase. The Processing phase was computationally fast, as it was based on a single uniform input format of the files produced by the Parsing phase, and it included the performance of the bulk of the analysis described below, which could be done with various sets of parameters.

2. Definitions

D_1: Minimum magnitude of frequency drop for the event to be considered a potential contingency in the Parsing phase. If the frequency drop of this magnitude took place between two frequency values up to 6 seconds apart, the latter value was identified as the start of a contingency. D_1 has a low value to create a very inclusive initial sample set.

D_2: Minimum magnitude of frequency drop for the event to be considered a potential contingency in the Processing phase. If the frequency drop for the event between points X and Y shown in Figure 27 was less than this magnitude, then the sample in question was discarded.

F_{high}: This parameter was used in the Processing phase. If point Y was above this bound, the sample was discarded.

F_{end}: This parameter was used in the Processing phase. The first point after point Y in the frequency trend that rose above this threshold was considered point Z.

t_{min}: This parameter was used in the Processing phase. If the time difference between point Y and point Z was less than this value, the sample was discarded.

FR: This is the Interconnection frequency response, calculated as described in section V.

F_X: Frequency error at point X.

F_Y: Frequency error at point Y.

F_Z: Frequency error at point Z.

t_X: Timestamp of point X.

t_Y: Timestamp of point Y.

t_Z: Timestamp of point Z.

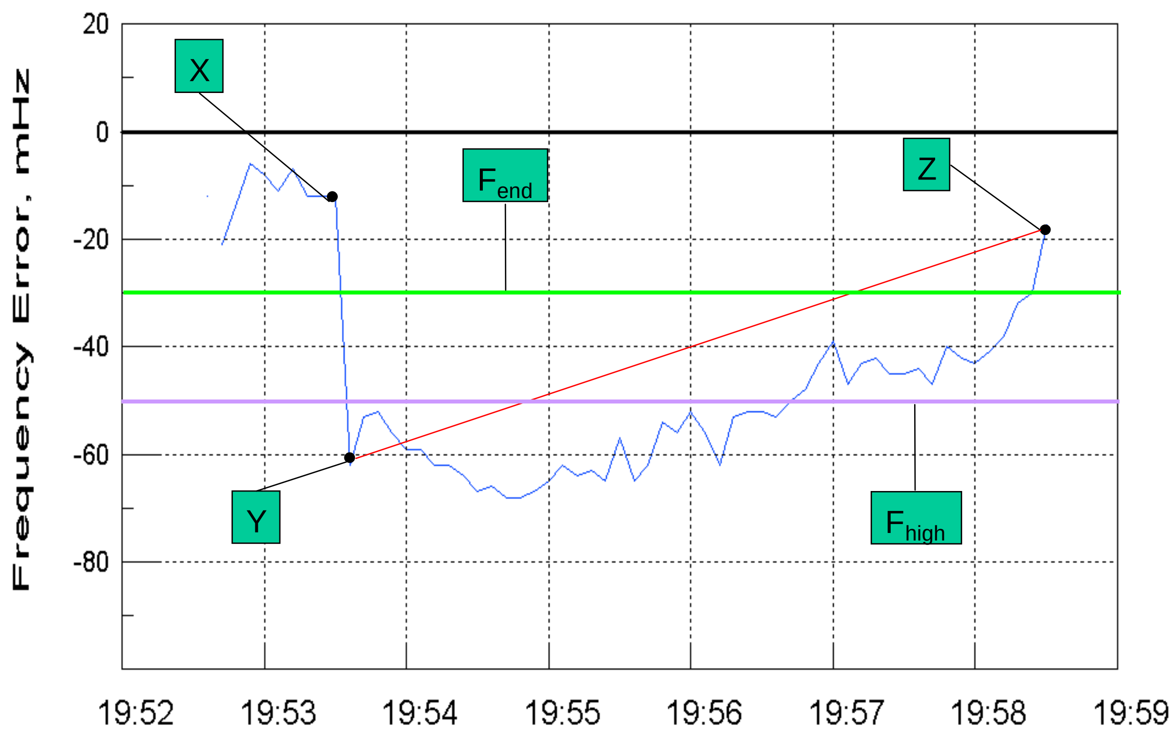

Figure 27. Plot of a recovery following a contingency, showing some significant points and parameters considered by the Processing phase program for this event.

3. Parsing Phase

The algorithm for this first phase read data from one of several frequency sources (one for Eastern Interconnection, one for ERCOT, and two for WECC), isolated potential contingencies, and created an output data set containing a large number of frequency trends with characteristics of contingency operation, which allowed for quickly running the Processing phase under most conceivable parameter sets.

It scanned through a chronologically ordered set of data files for potential contingencies in the frequency trend using a relatively small frequency drop as the threshold for defining a contingency. If there was a drop of D_1 over 6 seconds, the algorithm logged the timestamp associated with the last data as the start time of the potential contingency, the previous 60 seconds of frequency data, and the next 900 seconds of frequency data or the time until the next contingency, whichever was shorter (including the frequency value that satisfied the D_1 condition). The output of this phase served as input to the next phase. Prior to starting the

Processing phase, PCE verified the contingencies found in the Parsing phase and eliminated data likely to include significant telemetry errors.

4. Processing Phase

The algorithm for the second phase was designed to find which samples collected in the previous phase met a specified profile, find points X, Y, and Z for that sample, and calculate the recovery rate (in MW/min) as

$$Rate = -FR \times \frac{(F_Z - F_Y)}{(t_Z - t_Y)} \qquad \text{(D-1)}$$

Determining Point X

To find point X, the algorithm took the frequency error at 6 seconds before the data marked as the start of the contingency data in the file provided in the Parsing phase above.

Determining Point Y

To find point Y, the algorithm initially took the data marked as the start of the contingency data in the file provided in the Parsing phase above. If the frequency error at the next data point was greater than F_Y, it was considered the initial point Z. Otherwise, it was considered the new point Y. If the frequency did not begin to increase within 12 seconds of t_X, the sample was discarded. If the difference between F_X and F_Y was less than D_2, or if F_Y was greater than F_{high}, the sample was discarded, as it was likely that the amount of expected recovery would be so small as to introduce a disproportionate amount of noise in the final result. If F_Y was less than -800 mHz, the sample was discarded, as the data was likely to be invalid.

Determining Point Z

To find point Z, the algorithm started from the initial point Z found in the previous step. The algorithm then stepped through the remaining data points (for up to 600 seconds of data) and at each step, compared the frequency error to the provisional value of F_Z. If the frequency error at that data point was greater than F_Z, then that data point became the new point Z. If this point Z was greater than F_{end}, then this was marked as the final point Z. Thus, point Z was either the first frequency error greater than F_{end}, or, if no such value existed, the highest frequency error in the period considered following the contingency.

Determining Sample Recovery Rate

If the difference between t_Z and t_Y was at least t_{min} seconds, then rate was determined according to Equation D-1, using points Z and Y given above, and *FR*.

Determining Interconnection Recovery Rate

Once all sample rates were determined, the average of the sample rates for all valid events over the latest available three years of data was used as the recovery rate for the interconnection in determining the Minimum Safe Megawatt Deadband.

5. Choosing Algorithm Parameters

PCE proceeded to select appropriate values for the parameters for the various Interconnections. PCE set:

- D_1 and D_2 using experience gained in analyzing frequency data, erring on the side of caution to avoid including frequency drops not caused by contingencies.
- t_{min} to 12 seconds for all Interconnections in order to avoid inclusion of samples with questionable swings of frequency.
- F_{high} for each Interconnection to a value where a significant governor and secondary response was necessary to move the post contingency frequency to a level higher than F_{end}.

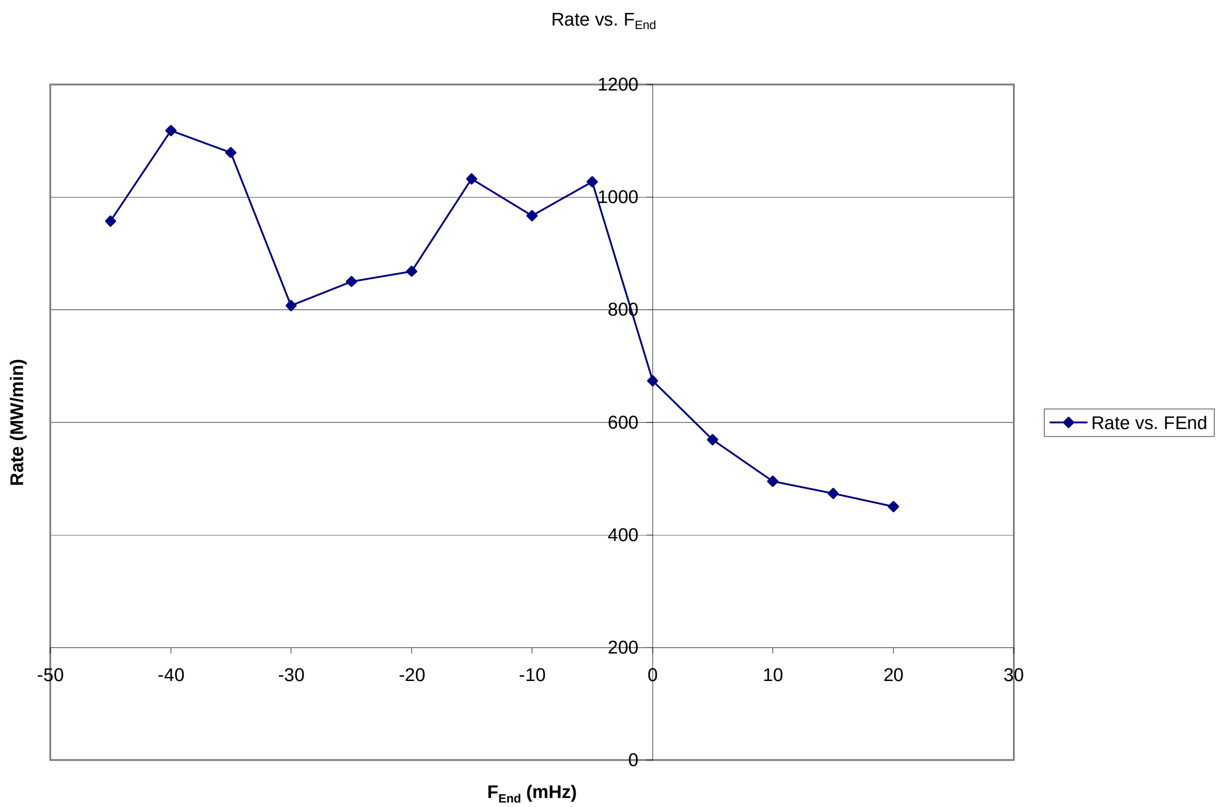

Figure 28. Plot of recovery rate vs. F_{end} for the Eastern Interconnection.

In order to select F_{end}, PCE analyzed data for various possible values of that variable to select a conservative estimate. To give an example of that approach, Figure 28, above, shows the chart of recovery rate plotted against various values of F_{end} for the Eastern Interconnection. The actual recovery rate used to calculate Minimum Safe Megawatt Deadband was chosen based on F_{end} of -30 mHz. Values greater than -10 mHz created inaccurate results, as the rate of frequency increase necessarily declined when Interconnection reliability was no longer threatened. Of the more realistic possible values of F_{end} below -10 mHz, -30 mHz provided the most conservative estimate of recovery rate.

The following parameters were used for the Eastern Interconnection:

D_1	-20 mHz
D_2	-30 mHz
F_{high}	-50 mHz
F_{end}	-30 mHz
FR	-3,109 MW/0.1 Hz
t_{min}	12 s

Using these parameters, the recovery rate for the Eastern Interconnection was found to be 807 MW/min.

The following parameters were used for the WECC Interconnection:

D_1	-20 mHz
D_2	-45 mHz
F_{high}	-60 mHz
F_{end}	-30 mHz
FR	-969 MW/0.1 Hz
t_{min}	12 s

Using these parameters, the recovery rate for the WECC Interconnection was found to be 403 MW/min.

The following parameters were used for the ERCOT Interconnection:

D_1	-30 mHz
D_2	-60 mHz
F_{high}	-80 mHz
F_{end}	-40 mHz
FR	-419 MW/0.1 Hz
t_{min}	12 s

Using these parameters, the recovery rate for the ERCOT Interconnection was found to be 146 MW/min.

Appendix E. Directed Research Tasks for NERC Balance Resources and Demand Standard

The following is a list of all tasks defined in the full "Directed Research for Balance Resources and Demand Standard's Procedures for Developing Frequency-related Limits" document provided to PCE [3]. They have been enumerated for ease of referencing.

1. Validation of Frequency Limits

1.1. Validate the Concept of Using Probabilistic Acceptable Risk Limits, Based on Unwarranted Under Frequency Load Shedding and Unit Outages

The process for developing frequency limits is based on the concept of utilizing a probabilistic acceptable risk limit based on unwarranted under frequency load shedding and the probability of generating unit outages. This concept should be examined to ensure that it is technically sound and practically feasible.

1.2. Validate the Concept of Using Interconnection Frequency Response to Estimate Response to Generation/Load Mismatches

The process for developing frequency limits calculates an Interconnection frequency response and then uses this frequency response to estimate the Interconnection's response to generation/load mismatches. This concept should be examined to ensure that it is technically sound and practically feasible. Specific areas for research include:

1.2.1. Use of lagging (historical) vs. leading (predictive) indicators to be utilized for estimate.

1.2.2. Accuracy, variability, and sensitivity of Interconnection frequency response with respect to various parameters such as time of day, time of year, load level.

1.2.3. Behavior under stressed conditions — whenever frequency levels fall below XXX or above ZZZ for each interconnection.

1.3. Validate the Concept of Using Frequency-related Relay Settings to Establish Interconnection-wide Limits

Examine the concepts and practices utilized by the industry to determine if such limits are suitable for use in a risk-based reliability standard. Specific areas for research include:

1.3.1. Technical validation of the process (Regional identification and authorization of each frequency-related relay setting within its footprint.)

1.3.2. Determine if there are NERC Regional variations and if there are NERC Regional variations, identify how they affect the process of determining Interconnection limits.

1.4. Validate the Concept of Using Supply-side Contingencies to Estimate Interconnection Reliability Risk

The process for developing each Interconnection's Frequency Abnormal Limit Low is based on the concept of using supply-side (generation) contingencies. This concept should be examined to ensure that it is technically sound and practically feasible. Specific areas for research include:

1.4.1. Technical validation of the concept of using contingencies to estimate Interconnection reliability risk.

1.4.2. Accuracy, variability, and sensitivity of estimates of Interconnection risk using available contingency information for each of the Interconnections.

1.4.3. Impact of multiple coincident contingencies, particularly those associated with loss of plant and loss of right-of-way conditions.

1.4.4. Robustness of process and behavior under stressed conditions.

1.5. Validate Steps in Process for Developing Frequency Limits

Validate the process for developing frequency limits (Attachment A) by following the steps in the draft Balance Resources and Demand Standard Requirement 305. This validation should specifically show whether the procedure can be followed to develop a set of frequency limits, including all of the following, for the Eastern Interconnection, the Western Interconnection, and ERCOT:

1.5.1. Frequency Trigger Limit $_{High}$ and associated Frequency Trigger Limit $_{High}$ Tv

1.5.2. Frequency Trigger Limit $_{Low}$ and associated Frequency Trigger Limit $_{Low}$ Tv

1.5.3. Frequency Abnormal Limit $_{High}$

1.5.4. Frequency Abnormal Limit $_{Low}$

1.5.5. Frequency Relay Limit $_{High}$

1.5.6. Frequency Relay Limit $_{Low}$

1.6. Validate that the Frequency Limits Work as Intended

Provide examples showing how various sized Balancing Authorities in each of the three major Interconnections would be affected by the proposed frequency limits under a variety of operating scenarios.

2. Validation of Process for Developing Balancing Authority ACE Limits (BAALs)

2.1. Validate the steps in the process for developing Balancing Authority ACE Limits

Validate the formula and practical implications of using a megawatt ACE limit for each Balancing Authority in order to ensure frequency-related reliability on each of the Interconnections. Specific areas for research include:

2.1.1. Reserve Sharing Groups.

2.1.2. Impact on Balancing Authorities of different sizes.

2.1.3. Impact of NERC Regional differences.

2.1.4. Impact on various wholesale markets (i.e. PJM and MISO).

2.1.5. Robustness of process and behavior under stressed conditions.

2.2. Validate that the Balancing Authority ACE Limits Work as Intended

Provide examples showing how various sized Balancing Authorities in each of the three major Interconnections would be affected by the proposed Balancing Authority ACE limits under a variety of operating scenarios.

Appendix F. Directed Research Status and Conclusions

The BRD SDT has defined the objectives listed in the left column of Table 7 below for validating the Standard (Appendix E contains the complete description of Directed Research objectives specified by NERC). CERTS has subcontracted PCE to prioritize addressing these objectives and perform research toward as many of those deemed most important as possible within the resources available for this project. The right column of that table summarizes the issues and conclusions resulting from the work performed toward these objectives in Phases I and II, and marks those tasks subject to future research.

Table 7. Tasks, conclusions, and next research steps for Directed Research objectives.

NERC BDR SDT Directed Research Scope	Derived Tasks	Conclusion or Next Research Steps
1) Validate the Concept of Using Probabilistic Acceptable Risk Limits, Based on Unwarranted Under Frequency Load Shedding and Unit Outages	a) Use of probabilistic acceptable risk limits, based on unwarranted under frequency load shedding and unit outages	The concept of using unit outage statistics and a probabilistic approach to evaluate and limit the rate of load shedding due to the activation of UFLS relays is sound. As long as frequency does not go beyond FAL during non-contingency operation, the risk of activating under- and over-frequency relays should remain within the targeted bounds. While the measures in the Standard have some correlation with bounding frequency to FAL, compliance with them is not sufficient to confidently predict the rate at which frequency can exceed FAL and, hence, FRL. In addition to unit outage rates, factors such as future generation control practice can affect the risk of frequency reaching FAL and, hence, FRL. The impact of these factors is complex, interdependent, and outside the scope of this study. Consequently, the method for developing frequency limits proposed in the Standard and followed in this report does not set FTL to such an optimum value that compliance with all the measures ensures this risk is bounded to a statistical target. The research presented in this report has shown that the requirements and measures of this Standard could be improved considerably. Given the conservative method of setting FAL, NERC may proceed with implementing the Standard, taking into account the additional constraints on setting FTL discussed in this report. In that case, however, NERC will need to continue monitoring frequency performance and quickly tighten FTL_{high}, FTL_{low}, T_{vb}, T_{vfh}, and/or T_{vfl} if future practice causes frequency to exceed FAL too often.

Table 7. Tasks, conclusions, and next research steps for Directed Research objectives; cont'd.

NERC BDR SDT Directed Research Scope	Derived Tasks	Conclusion or Next Research Steps
		As one of the considerations, it may be necessary to limit the FTL for each Interconnection to a setting in the range of 3 to 4 times of its ε_1 in order to help one-minute average frequency error to meet the targeted RMS as required by the SAR. This constraint should also help prevent a large growth in the shedding rate of non-firm loads in WECC. It may also be useful to perform a study of the errors in ACE and frequency measurements, and their potential impact on the risk of reaching FRL under the Standard.

Table 7. Tasks, conclusions, and next research steps for Directed Research objectives; cont'd.

NERC BDR SDT Directed Research Scope	Derived Tasks	Conclusion or Next Research Steps
2) Validate the Concept of Using Interconnection Frequency Response to Estimate Response to Generation/Load Mismatches	a) Calculation of frequency response from available data.	It is technically feasible to estimate frequency response from available data. This report calculates and utilizes a measure of frequency response, termed P-Frequency-Response, that uses the largest observed deviation of frequency for each historical contingency event in order to estimate the maximum frequency deviation expected for a given generation or load loss. PCE estimated the P-Frequency-Response for three NERC Interconnections. Methods to improve the accuracy of the calculation of the Minimum Safe Frequency Deadband are discussed in this report.
	b) Use of historical vs. predictive indicators to be utilized for estimate	PCE used available 2-6 second historical frequency data to estimate the P-Frequency-Response for three NERC Interconnections. Impact of potential decline of P-Frequency-Response on the risk of reaching FRL is subject to future research.
	c) Accuracy, variability, and sensitivity of frequency response with respect to various parameters	Analysis of the impact of variations in P-Frequency-Response on the risk of reaching FRL associated with contingencies is subject to future research. For estimating the relevant frequency departure resulting from the final contingency, the process should consider only the portion of the primary response that is realizable before UFLS relays activate.
	d) Behavior under stressed conditions, such as large frequency error	This is subject to future research.

Table 7. Tasks, conclusions, and next research steps for Directed Research objectives; cont'd.

NERC BDR SDT Directed Research Scope	Derived Tasks	Conclusion or Next Research Steps
3) Validate the Concept of Using Frequency-related Relay Settings to Establish Interconnection-wide Limits	a) Using frequency-related relay settings to establish interconnection-wide limits	PCE has verified that region-approved UFLS settings exist. They can be used to set FRL_{low} and doing so is sound in terms of the reliability objectives defined in the Standard. There may be other factors that should influence the setting of FAL and FTL, and deserve additional study. One is maintaining the frequency profile of the Interconnection within the targeted bounds. It is not clear that CPM-1 alone will be sufficient to accomplish this goal. Another is the impact on the shedding rate of non-firm loads. Validation of the concept for over-frequency relay limits is subject to future research.
	b) Examine industry UFLS practices and settings	PCE has obtained UFLS data for all Eastern Interconnection regions, WECC, and ERCOT.
	c) Regional identification of UFLS relay settings in NERC regions	PCE recommends that a measure be added to the Standard to require all NERC regions or RCs to submit all under- and over-frequency relay settings approved by them or utilized in their territory whenever such settings change. This will ease the job of the NERC working group who will become responsible for updating parameters of the Standard on a regular basis.
	d) Authorization of UFLS relay settings in NERC regions	PCE recommends clarifying the phrase "approved (firm load) Under Frequency Load Shed relay setting" in step (i) of the Frequency Limit calculation process described in [1] by elaborating on the word "approved". Changes in what relay settings are considered “approved” can have a significant impact on the values of FRL, FAL, and FTL.

Table 7. Tasks, conclusions, and next research steps for Directed Research objectives; cont'd.

NERC BDR SDT Directed Research Scope	Derived Tasks	Conclusion or Next Research Steps
	e) Impact of NERC Regional variations.	Highest UFLS settings have generally been found to be part of an SPS for local protection. There are loads in WECC and ERCOT that are set to shed at frequencies higher than the proposed FRL_{low}. These settings were not used to set FRL in those interconnections, but may need to be considered to prevent a large growth in their shedding rate.

Table 7. Tasks, conclusions, and next research steps for Directed Research objectives; cont'd.

NERC BDR SDT Directed Research Scope	Derived Tasks	Conclusion or Next Research Steps
4) Validate the Concept of Using Supply-side Contingencies to Estimate Interconnection Reliability Risk	a) Calculation of the risk of reaching UFLS limits due to supply-side contingencies	For any given frequency, it is technically feasible to calculate the risk of reaching UFLS relay limits due to generator trips and a method of doing that has been identified, implemented, and used for this research. Historical frequency data and contingency reports reveal that the largest supply-side contingencies in WECC and ERCOT are due to RAS activation or transmission loss, leading to separation of generators from the Interconnection.
	b) Accuracy, variability, and sensitivity of risk estimates using contingency information	No specific sensitivity analysis was performed and is subject to future research. The proposed process can be modified to take into account the impact of varying generation at the time of trip on Interconnection risk.
	c) Impact of multiple coincident contingencies, resulting from loss of plants and right-of-way	PCE has considered loss of multi-unit plants in its method of estimating risk due to generation contingencies. Data regarding historical failure statistics of DC transmission lines and converters, if available, could be added to the input data to improve the estimate of risk due to supply-side contingencies.
	d) Robustness of process under stressed conditions	This is subject to future research.

Table 7. Tasks, conclusions, and next research steps for Directed Research objectives; cont'd.

NERC BDR SDT Directed Research Scope	Derived Tasks	Conclusion or Next Research Steps
5) Validate Steps in Process for Developing Frequency Limits	a) Developing Frequency Trigger Limit_{high} and associated T_{vfh}	The current procedure for setting T_{vfh} does not have a strong correlation with the objectives of the Standard. Developing alternative measures or methods for setting T_{vfh} is subject to future research. T_{vfh} for all Interconnections has been provisionally set to the maximum limit of 30 minutes specified by the Standard. Additional research is necessary to establish FTL_{high} for all Interconnections.
	b) Developing Frequency Trigger Limit_{low} and associated T_{vfl}	The process for setting FTL_{low} has been followed for all Interconnections. WECC FTL_{low} can be anywhere from 59.856 Hz, when all generation trip events caused by loss of transmission facilities and those associated with RAS and SPS are ignored, to 60.075 Hz, when all such trips are included. It may be beneficial to set FTL_{low} about 3 to 4 times ε_1 below scheduled frequency. In addition to helping Interconnections frequency to remain in compliance with CPM-1, such a constraint in setting FTL_{low} should help prevent a large growth in the rate of shedding of some loads whose UFLS settings are much higher than FRL_{low}. The current procedure for setting T_{vfl} does not have a strong correlation with the objectives of the Standard. Developing alternative measures or methods for setting T_{vfl} is subject to future research. T_{vfl} for all Interconnections have been provisionally set to the maximum limit of 30 minutes specified by the Standard.
	c) Developing Frequency Abnormal Limit_{high}	Establishing FAL_{high} for all Interconnections is subject to future research.

Table 7. Tasks, conclusions, and next research steps for Directed Research objectives; cont'd.

NERC BDR SDT Directed Research Scope	Derived Tasks	Conclusion or Next Research Steps
	d) Developing Frequency Abnormal $Limit_{low}$	FAL_{low} has been calculated for three NERC Interconnections using probabilistic generation loss data.

Table 7. Tasks, conclusions, and next research steps for Directed Research objectives; cont'd.

NERC BDR SDT Directed Research Scope	Derived Tasks	Conclusion or Next Research Steps
	e) Developing Frequency Relay $Limit_{high}$	Additional research is necessary to establish FRL_{high} for all Interconnections.
	f) Developing Frequency Relay $Limit_{low}$	PCE has established FRL_{low} for the Eastern, WECC, and ERCOT Interconnections using UFLS guidelines from NERC Regions.

Table 7. Tasks, conclusions, and next research steps for Directed Research objectives; cont'd.

NERC BDR SDT Directed Research Scope	Derived Tasks	Conclusion or Next Research Steps
6) Validate that the Frequency Limits Work as Intended	a) Provide examples showing the impact of proposed frequency limits on various sized BAs under a variety of operating scenarios	This is subject to future research.

Table 7. Tasks, conclusions, and next research steps for Directed Research objectives; cont'd.

NERC BDR SDT Directed Research Scope	Derived Tasks	Conclusion or Next Research Steps
7) Validate the steps in the process for developing Balancing Authority ACE Limits	a) Validate the formula for the proposed BA ACE limit	The proposed BAAL formulation is based on an assumption that risk of reaching FRL is proportional to frequency deviation from schedule. The analysis presented in this report challenges this assumption. PCE has verified that the proposed BAAL formulation ensures that if all BAs are within their BAAL at all times, the Interconnection frequency will not exceed FTL. Therefore, for frequency to exceed FTL, at least one BA must be outside its BAAL. However, these features are not unique to the selected BAAL formulation; many different sets of formulations would have the same properties. Additional research is necessary to determine the optimum BAAL formulation. If scheduled frequency is replaced with 60 Hz in the proposed BAAL formulation, the properties described above will no longer hold during periods of time error correction.
	b) Practical implications of using the proposed BAAL	The proposed BAAL measures may not be sufficient to constrain the risk of reaching FRL to the targeted bounds as discussed in 8.a. They may also require disproportionately more control from smaller BAs than larger BAs as discussed in 8.b.
	c) Impact on Reserve Sharing Groups	This is subject to future research.
	d) Impact on BAs of different sizes	This is subject to future research.
	e) Impact of NERC Regional differences	BAAL measures may not have added reliability value for single-BA Interconnections, such as ERCOT.

Table 7. Tasks, conclusions, and next research steps for Directed Research objectives; cont'd.

NERC BDR SDT Directed Research Scope	Derived Tasks	Conclusion or Next Research Steps
	f) Impact on various wholesale markets	This is subject to future research.
	g) Robustness of process and behavior under stressed conditions	This is subject to future research.

Table 7. Tasks, conclusions, and next research steps for Directed Research objectives; cont'd.

NERC BDR SDT Directed Research Scope	Derived Tasks	Conclusion or Next Research Steps
8) Validate that the Balancing Authority ACE Limits Work as Intended	a) Show whether the proposed BAALs have the intended reliability impact	Requiring each BA to limit the number of consecutive minutes that its ACE exceeds BAAL to T_{vb}, as proposed by the Standard, is not sufficient to confidently limit the risk of frequency reaching FRL to a targeted value. One or more BAs can allow the magnitude of their ACE to increase in a way that causes the Interconnection frequency to reach FRL, but return their ACE inside BAAL within T_{vb} to ensure that they do not incur a violation. Nor has the above requirement been shown to be necessary to achieve the stated objective of limiting the expected rate of reaching FRL to once in 10 years.
	b) Provide examples showing the impact of proposed BAAL on various sized BAs under a variety of operating scenarios	PCE preliminary analysis indicates that the proposed BAAL equation may result in a decreased number of violations as a result of aggregate reporting of ACE. This may mean fewer expected violations for larger BAs for the same proportional amount of control and induced Interconnection risk. PCE recommends that this area be further explored in future research.

Appendix G. References

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