Frequency Control Requirements for Reliable Interconnection Frequency Response

Executive Summary

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Executive Summary

Prepared for the
Office of Electric Reliability
Federal Energy Regulatory Commission

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# Table of Contents

Acknowledgments ........................................................................................................................................... i

Table of Contents ............................................................................................................................................... ii

Table of Figures ............................................................................................................................................. iii

List of Tables ................................................................................................................................................... iii

Acronyms and Abbreviations .............................................................................................................................. iv

Executive Summary ............................................................................................................................................. 1

  Review of Frequency Control Concepts ........................................................................................................ 2
  Analysis Approach ........................................................................................................................................... 3
  Study Findings ................................................................................................................................................ 4
  Observations ................................................................................................................................................ 10
  Recommendations ......................................................................................................................................... 14

References ......................................................................................................................................................... 18

Appendix A. Glossary of Terms ........................................................................................................................ 21
Table of Figures

Figure ES - 1. The Sequential Actions and Impacts on System Frequency of Primary, Secondary, and Tertiary Frequency Control.................................................................3
Figure ES - 2. Frequency is Arrested when the Amount of Primary Frequency Response Delivered Equals the Amount of Generation Lost (2%)........................................................................5
Figure ES - 3. System Inertia and the Speed of Primary Frequency Response Determine the Nadir at Which Frequency is Arrested..................................................................................6
Figure ES - 4. Failure to Sustain Sufficient Primary Frequency Response Will Trigger UFLS ..................7
Figure ES - 5. The Relative Impacts of Generation Loss versus System Inertia on Frequency Nadir........11
Figure ES - 6. Frequency of the Eastern Interconnection during the First 199 Seconds Following the Loss of 4,500 MW of Generation—A Comparison of Recorded Data with Results from a Simulation of the Event........................................................................................................13
Figure ES - 7. Comparison of Selected U.S. and International Grid Codes Related to Frequency Response ..........................................................................................................................15

List of Tables

Table ES - 1. Interconnection Frequency Response Design Criteria at Times of Minimum System Load .. 11
Acronyms and Abbreviations

ACE  Area control error
AGC  Automatic generation control
BA   Balancing Authority
CAISO California Independent System Operator
CCGT Combined-cycle gas turbine
CCST Combined-cycle steam turbine
DOE  United States Department of Energy
Efrac Electronically coupled fraction of generation
ERCOT Electric Reliability Council of Texas
ERSWG Essential Reliability Services Working Group
FERC Federal Energy Regulatory Commission
GE   General Electric
GT   Gas turbine
GW   Gigawatt
Hydro Hydro-electric turbine
Hz   Hertz
ISO  Independent system operator
LBNL Lawrence Berkeley National Laboratory
mHz  millihertz
MW   Megawatt
NERC North American Electric Reliability Corporation
Nfrac Non-responsive fraction of generation
NREL National Renewable Energy Laboratory
PFRi Primary frequency response
Rfrac Responsive fraction
ROCOF Rate of change of frequency
Sfrac Sustaining fraction
Steam Steam turbine
UFLS Under-frequency load shedding
WECC Western Electricity Coordinating Council
Executive Summary

The reliability of interconnected electric power systems depends on controlling power system frequency so that it remains within pre-established, safe operating bounds. Reliability is threatened when a large electric generator(s) disconnects from the power system because the loss of generation causes an immediate decline in power system frequency. If the loss of generation is large enough and the remaining, still-connected generators do not respond and rapidly arrest the decline in frequency, power system frequency may decline below established, safe operating bounds and trigger automatic, emergency load shedding to avoid a cascading blackout.

The collective ability of the power system to respond to such events is called interconnection frequency response. Advance planning is required to operate the power system in a manner that ensures reliable frequency response at all times because generation-loss events are always unpredictable even though they occur relatively often.¹

The Federal Energy Regulatory Commission (FERC) has tasked Lawrence Berkeley National Laboratory (LBNL) to conduct this study to support ongoing FERC and industry efforts to ensure reliable interconnection frequency response for the three major interconnections in the United States: the Western, Eastern, and Texas Interconnections.² The purpose of this study is to support policymaker and industry understanding of the physical requirements for reliable interconnection frequency response by building upon an initial study conducted by LBNL for FERC in 2010.³ Improved understanding is especially timely now for several reasons.

First, industry experience with the frequency response-related requirements in the North American Electric Reliability Corporation (NERC) Reliability Standard BAL-003-1.1 (Frequency Response and Frequency Bias Setting), which mandates an interconnection-wide frequency response obligation is nascent. Increased understanding of the physical requirements for reliable interconnection frequency response will support industry efforts to comply effectively and in a timely way. Understanding of these requirements will also support possible future efforts to revise BAL-003-1.1 as well as supporting standards and other related activities (e.g., generator interconnection requirements).

Second, industry and policymakers are currently grappling with the reliability implications of changes in the composition of the generation fleet. Deeper understanding of reliable interconnection frequency response is needed.

¹ Given the large number of generators in the three U.S. interconnections, generation-loss events of varying sizes take place routinely, on a weekly, if not more frequent, basis. The very largest events, however, are considerably less frequent and rarely take place more than once a year.
² Throughout this report, we refer to the interconnection operated by the Electric Reliability Council of Texas (ERCOT) as the “Texas Interconnection.”
³ In 2010, FERC commissioned LBNL to study the use of frequency response metrics for assessing the reliable integration of variable renewable sources of electricity generation. LBNL prepared a technical report supported by five stand-alone technical appendices (Eto et al. 2010, Undrill 2010, Martinez et al. 2010, Illian 2010, Mackin et al. 2010, and Coughlin, Eto 2010). All reports are available at: https://certs.lbl.gov/project/integration-variable-renewable-generation. This study will be referred to in this report as “LBNL’s 2010 Study.”
response will enable industry to focus on the requirements that they must manage—rapid and sustained primary frequency response—and thereby help guide appropriate focus on related issues, such as how reductions in system inertia increase these requirements.

Finally, industry recognizes the important role that generator turbine-governors currently play in interconnection frequency performance. Expanded understanding of frequency response will enable industry to focus on the most important factors for ensuring that turbine-governors contribute to reliable interconnection frequency response: the speed at which the fleet first delivers and then sustains primary frequency response. Greater understanding will, in turn, support industry discussion of related issues for reliable interconnection frequency response, such as the value of small deadbands.4

Review of Frequency Control Concepts

The sudden, unplanned loss of a large amount of generation is an important, periodic challenge for reliable management of interconnection frequency. While unpredictable, these events are commonly the result of a mechanical or electrical problem within a large generating plant that causes the plant to disconnect itself automatically from the grid. Loss of a large amount of generation causes an immediate decline in system frequency that is felt throughout an interconnection. If no corrective actions are taken, frequency declines until the power system collapses, and a cascading, widespread blackout ensues.

Four physical factors determine whether an interconnection will respond reliably—i.e., without triggering emergency, interconnection-coordinated, under-frequency load shedding (UFLS)—to a sudden loss of generation (see Figure ES - 1):

1. The size of the generation-loss event;
2. The interconnection’s inertia, which, in combination with the amount of generation lost, determines the initial rate of decline of frequency following an event (i.e., the rate of change of frequency [ROCOF]);
3. The speed with which other on-line resources5 respond to arrest and stabilize frequency (i.e., provide primary frequency control);6 and
4. The means by which other generators respond subsequently to restore frequency to its original scheduled value and to restore reserves to their original state of readiness (i.e., provide secondary and tertiary frequency control).

Reliable interconnection frequency response requires that frequency be arrested and stabilized above the highest set-point for UFLS. This report describes the relationships on which interconnection

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4 A deadband on a turbine-governor determines the size of frequency deviation at which delivery of primary frequency will begin.
5 Non-generation-based resources for primary frequency response, such as the Texas Interconnection’s reliance on a nearly instantaneous form of demand response, are also reviewed in this report.
6 This report refers to primary frequency control as an objective and primary frequency response as the means by which resources contribute to this objective.
frequency response requirements are based and the considerations that must be addressed to ensure that these requirements are met.

Figure ES - 1. The Sequential Actions and Impacts on System Frequency of Primary, Secondary, and Tertiary Frequency Control  
*Source: Eto, et al. (2010): Use of a Frequency Response Metric to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation*

**Analysis Approach**

We developed a highly flexible modeling approach to illustrate key relationships and interactions among the factors that influence interconnection frequency response. The approach aggregates generators according to whether they do or do not; (1) respond to frequency deviations (i.e., provide primary frequency response); (2) sustain primary frequency response and; (3) contribute inertia to the interconnection.

We implemented the modeling approach by conducting dynamic simulations using the General Electric (GE) Positive Sequence Load Flow tool, known as PSLF—the same commercially available tool that is currently in wide use by industry to conduct, among other things, production-grade studies of frequency response. By using a commercially available tool, we were able to study the performance of turbine-governors and plant load controllers for different types of generators (e.g., combined-cycle,
hydro, and steam) using the same models of these generators that are used by industry to conduct reliability studies for planning and operations.⁷

The models we developed allowed us to examine: (1) the interconnection requirements for primary frequency response; (2) the headroom available on generators, which establishes an upper bound on the amount of primary frequency response; (3) the rate at which turbine-governors deliver primary frequency response from this headroom; and (4) plant-specific control settings or operating factors that limit or withdraw primary frequency response early (i.e., before frequency has been stabilized). We also examined fast demand response, governor deadband settings, and load sensitivity (sometimes called load damping),⁸ which also contribute to frequency response. We directly compared the performance of our simplified study model to the production-grade models developed by industry for each interconnection to demonstrate that we can meaningfully capture the important features of frequency response as predicted by industry models.

This simplified approach does not consider certain complexities of the transmission system, such as the transient or dynamic behavior of power flows, propagation of the generation-loss event, transmission losses, and deliverability, among others, which can be the focus of studies involving the detailed models used by industry.

**Study Findings**

Our findings are organized into three broad groups: (1) confirmation of fundamental, but potentially not widely understood factors that determine the initial requirements for resources held to provide primary frequency control; (2) the importance of equal attention to ensuring primary frequency response is sustained, including illustrations of various means by which primary frequency response may not be sustained and therefore must either be modified to sustain response or augmented by other resources that will sustain their response; and (3) findings related to other primary frequency control topics, including fast demand response, governor deadband settings, and load sensitivity.

1. **Reserves held to provide primary frequency control must exceed the expected loss of generation.**

Interconnection frequency reflects the balance between generation and load. The rapid decline in frequency following a loss of generation results from the sudden imbalance between generation and load. The decline is arrested once the balance between generation and load has been re-established. See Figure ES - 2. This is not a new or novel finding of this study; however confirmation and illustration of it as a fundamental principle forms the basis for all subsequent findings in this study. Furthermore, prudence dictates that the total primary frequency response capacity held on-line should exceed the

---

⁷ We emphasize, however, that the modeling approach we developed was intentionally simplified in order to focus on the interactions among the central physical factors influencing and resource performance characteristics required for reliable interconnection frequency response. It is not intended to replicate all aspects of, nor hence displace the need for interconnection- and system-level modeling conducted by industry.

⁸ The majority of our simulations assumed no load sensitivity in order to focus attention on the relationship between primary frequency control provided by active sources, such as generators, and interconnection frequency response.
size of the design generation-loss event to acknowledge uncertainty in the actual performance of the fleet.

2. Primary frequency response must be delivered quickly, which requires many participating generators.

The reserve for primary frequency response must be allocated among generators with recognition of the amounts of primary response that each type of generator can produce in the few seconds that are available to arrest the decline of frequency. This recognition can best be achieved, and in practice can only be achieved, by allocating reserves across a number of generators, such that each needs to make a small contribution to the required cumulative response. This finding, too, is generally understood, but it may not be widely appreciated.

"...it is prudent to ensure to the extent technically practical, that all generators [should] have the capability to provide primary frequency response."

As a consequence, it is prudent to ensure to the extent technically practical, that all generators—both those that are directly coupled and those that are electronically coupled to the grid—have the capability to provide primary frequency response. Ensuring this capability provides maximum flexibility to grid operators to assign primary frequency response duty to generators as appropriate for the current grid operating conditions. Exceptions should be considered only on a case-by-case basis.

9 The principal focus of this study is on primary frequency response provided by generation resources. Separate findings on primary frequency response by non-generation resources and on the sympathetic, but changing, role of load sensitivity appear at the end of this section.
3. For a given loss of generation, system inertia and the timing of primary frequency response determine how frequency is arrested.

The key factors determining the nadir of frequency are (a) the effective inertia constant of the system, which determines the initial rate of decline of frequency; and (b) the rate at which generation is increased by primary frequency response. Lower system inertia will require faster primary frequency response. Understanding the expected dynamic performance of the reserves that are held to respond, therefore, becomes of greater importance. For example, if the reserves held are quick to respond, they may be adequate for a wide range of possible future generation loss scenarios and corresponding system inertias. If they are slow to respond, they may require augmentation by faster responding reserves. See Figure ES - 3.

![Figure ES - 3. System Inertia and the Speed of Primary Frequency Response Determine the Nadir at Which Frequency is Arrested](image)

Source: Developed by LBNL from Undrill (2018): Primary Frequency Response and Control of Power System Frequency

4. Primary frequency response must be sustained until secondary frequency response can replace it.

Much attention has been devoted to ensuring adequate primary frequency response over the initial seconds following the loss of generation. Due attention should also be devoted to ensuring primary frequency response is sustained during the period when frequency is stabilized following the formation
of the nadir. During this period, primary frequency response is required in order to stabilize frequency. It must, therefore, be sustained until secondary frequency response can replace it. If, during this period, primary frequency response is not sustained and is reduced to less than the amount of generation lost, frequency will again decline and UFLS will be triggered. See Figure ES - 4. This point is less well appreciated but of equal importance for reliable interconnection frequency response.

![Graph showing frequency response](image)

**Figure ES - 4. Failure to Sustain Sufficient Primary Frequency Response Will Trigger UFLS**

*Source: Developed by LBNL from Undrill (2018): Primary Frequency Response and Control of Power System Frequency*

There are several means by which primary frequency response may not be sustained. The first is through withdrawal of primary frequency response by the actions of plant load controllers, which override and reset the actions of the turbine-governor responding to frequency deviations. We describe this finding first because it is an action that is directed by the plant owner/operator. As such, it is one that can be corrected by a plant owner/operator, which we discuss in Finding 5. The second is through actions stemming from inherent dynamic characteristics of turbine generators. One example is exhaust gas temperature limits on gas turbines, which are intrinsic to the current design of these types of turbines. Unlike plant-level controllers, these actions cannot be overridden or corrected. We conclude by discussing what we have observed in published information on wind turbines providing what is called "synthetic inertia."

The bottom line is that, if primary frequency response from some sources will not be sustained, primary frequency response from additional sources will be required. The requirement is to stabilize frequency until primary frequency response can be replaced by secondary frequency response.
5. Plant load controllers operated in pre-selected load mode without frequency bias will withdraw and not sustain primary frequency response.

Plant load controllers establish the ranges around which turbine-governors operate in response to frequency. A logic commonly followed by these controllers seeks to maintain generation output in accordance with a pre-determined schedule. Consequently, when generation output increases because the turbine-governor responds to a decrease in interconnection frequency, the plant load controller overrides the turbine-governor and automatically restores output to the scheduled value. This results in primary frequency response being withdrawn, which negatively affects restoration of interconnection frequency.

6. Plant load controllers operated in pre-selected load mode with frequency bias will sustain primary frequency response.

The early withdrawal of primary frequency response by plant load controllers can be prevented by specifying a control logic that seeks to operate the generator at the scheduled value only when the frequency of the interconnection is at its normal operating value of 60 Hertz (Hz). That is, when frequency deviates significantly from 60 Hz, for example because of loss of generation on the interconnection, the plant load controller does not override the turbine-governor but instead allows the turbine-governor to continue delivering primary frequency response until system frequency returns to the nominal value. This control logic supports the restoration of interconnection frequency following a loss of generation.

7. Gas turbines may not be able to sustain primary frequency response following large loss-of-generation events.

Gas turbines are among the fastest responders that contribute to arresting the decline in system frequency following the sudden loss of generation. They can readily increase their output by a few percent of rated capacity within a handful of seconds (5 to 8 seconds). As a result, they are excellent initial sources of primary frequency response. However, if an under-frequency event calls for maximum output, this maximum will be less than would be reached when running at nominal frequency. Unlike the withdrawal of response by plant load controls, reduction of output is an action of the protection system of the turbine and cannot be deactivated at the discretion of the plant operator. There is feedback between these controls and system frequency that can be detrimental to reliable interconnection frequency response. That is, if, as exhaust gas temperature controls reduce turbine output, and system frequency continues to decline, then the temperature limit controls will further reduce turbine output. It is therefore essential to recognize this dependence of gas turbine maximum output on frequency and ensure that response is available from sources that will sustain or increase their response during the comparatively longer periods when system frequency may be depressed following large loss-of-generation events.
8. “Synthetic inertia” controls on electronically coupled wind generation appear not to sustain primary frequency response.

Inverter-based controls on electronically coupled generation sources (such as wind turbines, solar photovoltaics, and batteries) can provide sustained primary frequency response through a droop relationship in the same manner that turbine-governors operate in conventional power plants. In cases of low frequency, this requires reserving headroom from which the response is drawn. As an alternative, "synthetic inertia" controls are said to provide a form of primary frequency response without reserving headroom.

So-called "Synthetic inertia" controls on electronically coupled wind generation can have a similar impact as described above, in which primary frequency response is delivered but terminated before frequency is stabilized. This type of frequency response comes from the extraction of kinetic energy from spinning wind turbine blades. That is, the turbine blades slow down. Based on published information, the response, however, appears to be one that is not sustained and is, in effect, withdrawn within five to ten seconds. If this is unavoidable, then other sources of sustaining primary frequency response will be required that continue to stabilize frequency until secondary frequency response can replace them.

9. Fast demand response provides robust primary frequency response, but currently is inflexible.

Removing load immediately affects interconnection frequency and is therefore an effective strategy to restore the balance between load and generation after generation is lost. However, the amount of load shed—as well as the frequency at which it is shed and the time delay beforehand—must be established carefully in advance. If the amount of load shed is greater than the amount of generation that was lost, an over-frequency situation can result, which may also pose a severe challenge to system reliability.

10. Smaller deadbands on turbine-governors increase how quickly delivery of primary frequency response will begin.

Deadband settings on turbine-governors determine at what frequency deviation a generator will begin delivering primary frequency response. Smaller deadbands mean that a generator will respond to smaller generation-loss events than a generator with a larger deadband. Moreover, for larger generation-loss events, generators with smaller deadbands will begin responding sooner than generators with larger deadbands. Operating with smaller deadbands therefore will improve interconnection frequency response compared to operating with larger deadbands. Importantly, unequal deadbands among generators mean that those with smaller deadbands will begin responding sooner and more often than generators with larger deadbands. In the extreme, if a generator operates with a very large deadband (300 or 500 mHz), then the generator will only respond to the very largest generation-loss events (and may do so too late to avoid triggering UFLS). Such extreme deadband settings undermine the goal of providing frequency response because the turbine-governor will not respond to the vast majority of generation-loss events, which are smaller in size.
11. Load sensitivity currently complements primary frequency response, but this sensitivity may be going away.

Although a portion of load has traditionally reduced consumption autonomously in proportion to a decline in interconnection frequency and, hence, augmented the frequency response that generators provide, the characteristics of load are changing. In particular, load that is electronically coupled to the grid using power electronic interfaces is increasingly common. These loads include variable-frequency drives on motors, fans, and pumps. These electronically controlled forms of load can work to the detriment of frequency control because they generally act to prevent the power drawn from declining as frequency declines. Directly coupled motors "slow down" when frequency declines and reduce power consumption, and thereby work in concert with primary frequency response delivered by generators. By not slowing down and not reducing power consumption, electronically coupled motors no longer contribute or support primary frequency response delivered by generators. This impact of electronic controllers on interconnection frequency response, however, is not a given. Electronic controllers can be programmed to support reliable interconnection frequency response.

Observations

Texas Interconnection

Frequency response is a significant issue for the Texas Interconnection, and has been managed proactively by ERCOT for some time. On a percentage basis, the design generation-loss event for the Texas Interconnection—especially at times of minimum system load is nearly three times larger than the design generation-loss event at minimum system load for the Western Interconnection, and more than five times larger than the comparable event for the Eastern interconnection. (See Table ES - 1.) As a result, the design generation-loss event in the Texas Interconnection results in a much sharper and more rapid decline in frequency compared to the other two interconnections. (See Figure ES - 5.) These ROCOF values present a challenge for the frequency response obtainable from conventional power plants. Thus, ERCOT’s reliance on a fast form of demand response is important, if not critical, for ensuring reliable interconnection frequency response.

10 Because of these considerations related to load, our initial set of simulations removed the effects of load in augmenting provision of primary frequency control. This enabled us to obtain direct insight into the role of generators in responding to frequency excursions and ensured that our findings would be conservative.

11 The design generation-loss event is expressed as a percentage of the total system load at the time of the event.

12 Future forms of fast demand response could be more flexible than the current form of demand response relied upon by ERCOT. One form, illustrated in Section 5.9, might involve shedding smaller blocks of load at different frequency set points. Another form, alluded to in Section 5.11, might involve load that could be varied continuously in response to frequency changes in a manner analogous to droop control of turbine-governors.
### Table ES - 1. Interconnection Frequency Response Design Criteria at Times of Minimum System Load

<table>
<thead>
<tr>
<th>Design Criteria:</th>
<th>Eastern Interconnection</th>
<th>Western Interconnection</th>
<th>Texas Interconnection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation-Loss Event</td>
<td>4.5 GW</td>
<td>2.7 GW</td>
<td>2.7 GW</td>
</tr>
<tr>
<td>Minimum Load - 2015</td>
<td>210 GW</td>
<td>64 GW</td>
<td>24 GW</td>
</tr>
<tr>
<td>Gen. Loss Event/Min Load</td>
<td>2.1 %</td>
<td>4.1 %</td>
<td>11.3 %</td>
</tr>
</tbody>
</table>

*Source: Developed by LBNL from NERC (2017b): 2017 Frequency Response Annual Analysis; and Matevosyan (2016): Inertia Data*

**Figure ES - 5. The Relative Impacts of Generation Loss versus System Inertia on Frequency Nadir**

*Source: Developed by LBNL from Undrill (2018): Primary Frequency Response and Control of Power System Frequency*

Texas will likely lead the three U.S. interconnections in addressing the challenge of synchronous generating resources that provide primary frequency control being retired and replaced with generation from non-synchronous resources, such as wind and solar. One obvious solution is to find ways to engage the primary frequency control capabilities of the large and growing amount of wind and solar generation in the Texas Interconnection. However, doing so will require addressing the commercial arrangements that currently create strong financial incentives for wind and solar to operate without headroom. As noted above, “synthetic inertia,” which, based on the literature, is a form of primary frequency control provided by wind generation without reserving headroom and is then quickly withdrawn is not a substitute for sustained primary frequency response.
Western Interconnection

Frequency response is also a long-studied issue in the Western Interconnection. The Western Electricity Coordinating Council (WECC)-specific version of the NERC BAL standard (BAL-002.WECC-2a) states that the Western Interconnection’s spinning reserve requirements must be met by generation that is on-line and now clarifies that this generation must respond autonomously and automatically to changes in frequency. In other words, all spinning reserves in WECC must provide primary frequency response. In addition, the Western Interconnection has routine practices to update and validate the models used to support, among other things interconnection frequency response studies.

In the Western Interconnection, the geographic distribution of the reserves relied on for primary frequency control means that the transmission system plays a critical role in delivering frequency response. As discussed in LBNL’s 2010 Study, reliance on the long-distance transmission system poses a risk to reliable interconnection frequency response. The risk stems from the need to ensure that sufficient reserve capability is available on the transmission lines to reliably deliver primary frequency response to the area where generation was lost. Failure to maintain sufficient transmission reserve capability increases the risk that primary frequency response cannot be delivered and that UFLS will be triggered. This risk will increase if older, thermal-based reserves that provide primary frequency control located in the Southwest retire, leading to even more reliance on hydro-based reserves in the Northwest.

Retiring generation will of course be replaced with newer forms of generation. The character (and location) of this new generation will affect interconnection frequency control. For example, if older thermal generation is replaced by combined-cycle, wind, or solar generation that responds to frequency, primary frequency control capability in the Southwest could be maintained and could increase. The rules and incentives for generators to install, maintain, and make available primary frequency control capability will determine the outcome.

More recently, the Western Interconnection has experienced a new type of generation-loss event involving electronically coupled, inverter-based generators (solar PV). WECC and NERC are actively studying the implications of these events both for frequency response and other aspects of system control, including the means to address them (NERC 2017a).

Eastern Interconnection

Primary frequency control is a known issue in the Eastern Interconnection. This study’s findings clarify that the comparatively large size of the Eastern Interconnection relative to the number of generation-loss events explains the lower ROCOF values observed for these events compared to the ROCOF values observed in other interconnections after losses of comparable amounts of generation. This study also clarifies how the large number of generators providing primary frequency response also contributes to

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13 As an aside, the inertia of the interconnection would increase if older thermal generation is replaced with combined-cycle gas plants. For a given size generation plant, the inertia of a combined-cycle gas plant is higher than that of nuclear-, coal-, or gas-fired steam plants. See Figure 12.
measured frequency response of the interconnection.

Two aspects of primary frequency control are currently the focus of attention in the Eastern Interconnection. First, the characteristic “lazy L” shape of frequency response in the Eastern Interconnection is widely recognized as being driven by withdrawal of primary frequency response by plant load controllers. See Figure ES - 6. As noted in Section 3 of this report, this explanation has been corroborated in modeling studies conducted by both NERC staff and GE. Our study has shown that withdrawal can have a detrimental effect on interconnection frequency response and that, when it is caused by plant load controls, it is can be remedied. Therefore, it is important that industry monitor and, as appropriate, implement interconnection and region-specific operating policies and procedures that prevent excessive withdrawal of primary frequency response.

![Figure ES - 6. Frequency of the Eastern Interconnection during the First 199 Seconds Following the Loss of 4,500 MW of Generation—A Comparison of Recorded Data with Results from a Simulation of the Event](image)

*Source: Eto, et al. (2010): Use of a Frequency Response Metric to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation*

Second, the importance of primary frequency response withdrawal for the Eastern Interconnection is also a motivation to continue to improve the ability of the interconnection’s dynamic planning models to replicate and explain the interconnection’s observed frequency response. As noted first in LBNL’s 2010 Study and found again in Undrill, et al. (2018), the current Eastern Interconnection planning models do not reproduce the measured performance of the interconnection during a design generation-loss event (which is used to evaluate the adequacy of primary frequency control within the interconnection). We note that NERC staff is already working with planners in the Eastern
Interconnection to improve the quality of frequency response modeling (NERC 2017c).

Well-calibrated planning models are essential for assessing current performance and guiding modifications to interconnection agreements and operating policies to ensure continued, reliable interconnection frequency response. Continuous updating and ongoing calibration are essential for building confidence in applications of the models to study future scenarios involving changes in the mix of generation as well as load.

**Recommendations**

1. **Focused attention should be directed to understanding the aggregate frequency control performance required of the fleet of resources that must be kept on-line at all times to respond to generation-loss events. This will involve collection, maintenance, and validation of the data necessary for accurate planning and operating studies as well as collection of comprehensive data to measure trends in interconnection frequency control.**

The dynamic simulation tools and system models that the interconnections use to study frequency response must be based on accurate, up-to-date information about the actual characteristics of generators and load. This information should track not only interconnection loading, inertia, design generation-loss event, and highest set-point for UFLS, but also generator headroom, turbine-governor performance characteristics, and the number and location of resources for primary frequency control. Data are needed on the performance characteristics of non-traditional, non-governor-based resources for primary frequency response that indicate how much primary frequency response is available and how rapidly the response can be delivered. In the case of fast demand response, such as ERCOT’s Load Resources (an element of its Response Reserves Service), it is important to study the size of load blocks and the triggering conditions for them. Performance measures should apply equally to traditional and non-traditional resources. For all resources, this should entail explicit performance measures that assess the factors that might withdraw primary frequency response early or cause it to not be sustained.\(^{14}\) Simulation-based or other forms of study should consider the full period over which primary frequency response must be sustained—which may be as long as several minutes—and determine the rate at which non-sustaining response must be replaced in order to ensure reliable interconnection frequency response. Studies should examine worst-case situations involving either or both times of low system inertia and times when reserves of primary frequency control may be low.

Routine, comprehensive measurement of interconnection frequency control performance is essential for tracking trends.\(^ {15}\) This will require ongoing updating and verification of the performance of generators and other resources for primary frequency response as well as the conditions of the interconnection during which these resources are called upon. To the extent feasible, measurements should form the basis for the information used to model and plan for procurement and dispatch of resources that provide primary frequency response. As an example, performance measurements during

\(^{14}\) NERC’s ERSWG has developed and is currently tracking measures that seek to address this issue. See NERC 2015a.

\(^{15}\) In fact, NERC has become compiling and now regularly publishing this information. See, for example, NERC 2017b.
actual events should be the bases for establishing limits on procuring primary frequency response. This includes ensuring that modeling assumptions regarding primary frequency response capability are reflective of actual dispatch and power plant operating practices. In addition to tracking traditional measures of frequency response (such as interconnection frequency response), this process should document the conditions under which these measurements are made, such as the state of the power system (its loading and inertia, and whether load, and hence generation, is increasing or decreasing at the time generation is lost) and the size and location of generation-loss events relative to the performance of the primary frequency response resources, including the extent to which they sustain provision of primary frequency response.

2. **International practices should be reviewed as options for U.S. grid operators to consider adopting to ensure continued reliable interconnection frequency response.**

As the fleet of U.S. generation and the characteristics of load change, we must assess our approaches to frequency control to ensure that they continue to support reliable interconnection frequency response. Gaps, conflicts, and disincentives must be identified, analyzed, and addressed as appropriate.

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**Figure ES - 7. Comparison of Selected U.S. and International Grid Codes Related to Frequency Response**

*Source: Roberts (2018): Review of International Grid Codes*

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16 ERCOT, in fact, routinely conducts these measurements.
Our review of international frequency control practices spans a range of approaches that represent functioning alternatives to or variants of current U.S. approaches. Because of the demonstrated success of these approaches in other power systems, they should be reviewed, analyzed in current and expected future operating conditions in the United States, and then given due consideration for adoption, as is, or in modified form. See Figure ES - 7.

3. **All generators, to the extent feasible, should be capable of providing sustained primary frequency response.**

Reliable interconnection frequency response requires participation by many generators. Ensuring that as many generators as is technically feasible are capable of providing sustaining response provides maximum flexibility to grid operators to assign primary frequency response duty as appropriate for current grid operating conditions.

Moreover, reliability of the interconnections is enhanced by enabling this capability on all generators capable of providing sustained primary frequency response. Doing so increases the pool of responding generators and reserves of primary frequency response, and thereby reduces the risk of unforeseen shortages of primary frequency response. It is recognized that some generators will not contribute if they are already dispatched at maximum capacity and hence do not have headroom available.

4. **Barriers to adding a frequency bias\(^{17}\) to plant load controllers should be evaluated and addressed.**

This study describes the detrimental effects of early withdrawal of primary frequency response by plant load controllers. We also describe how early withdrawal of primary frequency response by plant load controllers can be prevented by introducing a frequency bias to the control logic of pre-selected load mode controls. We also recognize that some U.S. grid operators already require or have performance requirements that support the use of these controls. Still, others in the United States do not.

“...we recommend education and outreach as a minimum first step toward encouraging wider adoption of this control approach. In addition, it is important to understand and address any financial disincentives that would reinforce current practices.”

Anecdotally, we perceive that awareness of the efficacy of this alternative control logic is limited within the generator community. Accordingly, we recommend continued but expanded education and outreach to foster wider adoption of this control approach.\(^{18}\) In addition, it is important to understand and address any financial disincentives that would reinforce current practices.

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\(^{17}\) This use of the term “frequency bias” is distinct from the use of this same term in the Area Control Error equation that guides automatic generation control, which is a form of secondary frequency control.

\(^{18}\) NERC (2015a) is a good, initial example of this approach.
5. The contributions of non-traditional resources for primary frequency control (demand response, energy storage, and other forms of electronically coupled loads and generation, including wind and solar photovoltaics) should be studied and incorporated, as appropriate, into future operations.

One future change in the makeup of the generation fleet is that traditional resources for primary frequency response may retire and be replaced by non-traditional resources, including demand response, energy storage, and other forms of electronically coupled loads and generation such as wind and solar photovoltaics. The performance characteristics of non-traditional resources are not widely known or fully understood. Future frequency response-related operating and planning policies and decisions should be based on up-to-date, accurate information about the performance and potential contributions of these resources.\(^{19}\) Research, development, and demonstration are also needed to improve the performance capabilities of these new sources and to support timely industry adoption.

6. Factors that negatively influence the sensitivity of loads to frequency should be studied and addressed.

Load sensitivity historically complemented primary frequency response from generators. However, this sensitivity appears to be disappearing as newer forms of load are electronically coupled to the grid using power electronic interfaces, which currently do not reduce power consumption when frequency deviates from nominal. These forms of load include variable-frequency drives on motors, fans, and pumps. Better information is needed on how the frequency support provided by load changes over the course of a day and seasonally.

Still, no inherent technical limitations prevent power electronic interfaces from supporting primary frequency response by generators. In many instances, a simple firmware upgrade of power electronics controls is all that is required. The technical and commercial reasons that current controls do not provide primary frequency response should be understood and, where appropriate and feasible, modified or adjusted so that future loads will work in concert with and support primary frequency response from generators.

\(^{19}\) NERC’s Inverter Based Resource Performance Task Force may be one source for this information.
References


### Appendix A. Glossary of Terms

**Automatic generation control (AGC)**
An automated form of secondary frequency control that is used to oppose small deviations in system frequency around the scheduled value. AGC involves signals that are sent to plant-level controllers every 4 to 10 seconds to adjust a generator’s output in order to return interconnection frequency to its scheduled value.

**Frequency**
In North America, this is normally 60 cycles per second or 60 Hertz (Hz).

**Frequency control**
Primary or secondary frequency control refers to the aggregate effect of the actions of all generators participating in the control of interconnection frequency taking a control action.

**Frequency nadir**
The point at which frequency decline is arrested.

**Frequency response**
The collective ability of the power system to respond to frequency excursions, such as those caused by the sudden unplanned loss of generation.

**Governor**
The means by which generators provide primary frequency response; a governor’s actions are automatic (they do not depend on external commands) and autonomous (they do not depend on the actions of other generators).

**Headroom**
The difference between the current operating point of a generator or transmission system and its maximum operating capability. The headroom available at a generator establishes the maximum amount of power that generator theoretically could deliver to oppose a decline in frequency. However, the droop setting for the turbine-governor and the highest set point for UFLS will determine what portion of the available headroom will be able to deliver to contribute to primary frequency control.

**Inertia**
The ability of a power system to resist changes in frequency, measured in MW-seconds. Inertia is an inherent property or characteristic of each generator and element of load.

**Load sensitivity**
Loads that reduce their consumption of electricity in proportion to a decline in interconnection frequency, sometimes also called load damping.

**Plant load controllers**
External (to the turbine-governor) controls, taken together as a group.

**Primary frequency response**
Primary frequency response involves automatic, autonomous, and rapid (i.e., within seconds) changes in a generator’s output to oppose sudden changes in frequency; it refers to the actions of individual generators.

**Rate of change of frequency (ROCOF)**
A measure of how quickly frequency changes following a sudden imbalance between generation and load. ROCOF is expressed in Hertz per second (Hz/second).

**Secondary frequency response**
Directed (i.e., external or supervisory to the autonomous actions of the turbine-governor), slower actions to change a generator’s output to oppose changes in frequency.

**Settling frequency**
The point at which frequency is stabilized following formation of the nadir.
| **Tertiary frequency control** | Refers to centrally coordinated actions (i.e., it is a "manual" form of what we have called secondary control) that operate on an even longer time scale (i.e., minutes to tens of minutes) than primary frequency response and secondary frequency control provided through AGC. |
| **Under-frequency load-shedding (UFLS)** | An extreme measure to arrest frequency decline that disconnects large, pre-set groups of customers at predetermined frequency set points. |