GE Energy

Report

California ISO (CAISO)

Frequency Response Study

Final Draft

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imagination at work

FOREWORD

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EXECUTIVE SUMMARY

Frequency response, the response of the power system to large, sudden mismatches between generation and load, has recently been garnering a lot of attention across all four interconnections in North America. This study was specifically designed to investigate the frequency response of California due to large loss-of-generation events of the type targeted by NERC Standard BAL-003 – Frequency Response and Bias, under near future system conditions with high levels of wind and solar generation. While this study addresses the overall frequency response of the Western grid, it does not address any changes to the limits of stability-limited transmission paths that may be warranted at higher penetration of variable energy resources.

For this work, the California Independent System Operator (CAISO) created a number of credible loadflow and stability base cases that represent high penetration of wind and solar generation expected in California in the near future. These cases were deliberately selected with the expectation that they would represent some of the most challenging conditions for CAISO with respect to frequency response. The study primarily focused on two cases: A winter low-load and high-wind condition case, and a weekend morning high-wind and high-solar condition case. These cases represent different operating conditions with a large number of synchronous generators displaced by variable renewable energy resources. In addition, some of the thermal power plants with synchronous generators were also assumed to be retired due to once-through-cooling (OTC) regulation. At the snapshot of time represented in these cases, the fraction of California generation coming from wind and solar plants was 37% (11 GW total) and 50% (15 GW total), respectively. Most of the simulations focused on the trip of two units at the Palo Verde Nuclear Power Station. This 2690 MW event is the largest loss-of-generation event in WECC for which involuntary load shedding and other stability consequences must be avoided.

While the focus of the work was the frequency response of generators in California, it was critical to not only model the California system, but also the rest of the Western Electric Coordinating Council (WECC) system due to the interconnected nature of the grid. In this study, load flow cases were created in which wind generation was added to the US portion of the WECC outside of California, so that it represented 15% of the rest-of-WECC generation. The addition in wind generation was balanced by the de-commitment and re-dispatch of synchronous generation in the rest-of-WECC.

Numerous simulations were performed looking at factors expected to influence system frequency behavior, such as the fraction of generators with governor control (Kt) and headroom of governor responsive generation, controls on wind turbines, demand response and energy storage.

The key finding of the study is:

Frequency Response is not in crisis for California. None of the credible conditions examined, even cases with significantly high levels of wind and solar generation (up to 50% penetration in California), resulted in under-frequency load shedding (ULFS) or other stability problems. The system avoided UFLS with greater than 100 mHz margin in these cases. While the results of this analysis are based on credible, challenging system conditions, it is conceivable that under some extreme conditions not envisioned in this study, the system could have an unsatisfactory performance. Also, the study implicitly assumes that sufficient secondary reserves (regulation and load following) are available to handle the variability of wind and PV generation. If secondary reserves are exhausted due to uncertainty and variability associated with wind and solar generation, then primary frequency response capability may be drawn down before big events occur. While this study considered response and remediation for conditions of very low primary reserves, it did not attempt to quantify the specific causes or likelihood that such depleted primary reserve conditions might occur.

A brief summary of the other key findings and recommendations from the study are given below:

California's response to a large system event is generally above the frequency response obligation as presently proposed by the North American Electric Reliability Corporation (NERC) [1]. The fraction of generation participating in governor control, Kt, is a good primary metric for expected performance. The maneuverable capacity of frequency responsive generation, i.e. headroom, is also important, particularly when in short supply. Less than one third of committed generation in California contributes towards primary frequency response under some credible operating conditions. Low participation by the generation fleet should be investigated, and measures considered to increase it.

Governor withdrawal was found to cause a roughly 20% degradation in frequency response as measured by the NERC frequency response metric. Measures to correct this behavior should be investigated. Speed of primary response is important:

resources that provide significant incremental power before the frequency nadir are more valuable in avoiding load shedding.

Reduction in system inertia due to higher penetration of renewable generation, per se, may not have a significant impact on frequency response when compared with governor action. However, fast transient frequency support, via controlled inertial response from wind turbines, fast acting load response, or injection of power from energy storage all help increase the UFLS margin and avoid under-frequency load shedding. The benefit of these responses can be several times greater, per MW, than was observed for governor response in the synchronous fleet.

Several further investigations are recommended. WECC has some of the best dynamic model verification practices anywhere in the industry. Nevertheless, there is some *anecdotal* evidence that generators may be operating differently, e.g., with governors disabled and/or with load reference set-point controls enabled that defeat or diminish governor response. Detailed investigation of performance of individual units in response to actual grid events is recommended. As wind and solar generation penetration increase in California and throughout WECC, unit commitment and dispatch patterns will substantially depart from historical practice. For future planning analysis, commitment and dispatch that would occur under conditions of particular concern, i.e., periods of high wind and solar generation, relatively low load, possibly high inter-area exchanges and poor wind and solar forecasts, will need to be properly modeled. A separate project is starting to help facilitate better connection between the WECC energy management system and planning models.

While this study did not specifically evaluate CAISO's existing operating procedures and markets, it is distinctly possible that new market mechanisms will be needed in the future to assure adequate frequency response. In the absence of market mechanisms to assure adequate frequency response, CAISO will inevitably be forced to adopt defensive operational strategies, with possible adverse consequences including out-of-merit commitment and dispatch of responsive generation, curtailment of wind and solar generation, abrogation of power purchase agreements and may be subjected to fines levied for reliability violations. The market should reward fast, sustained frequency response. CAISO must stay engaged with NERC as definitions and requirements evolve.

Additional tools may be needed for operations. The fraction of generators with governor controls (Kt) and headroom are important means of measuring the system's ability to meet frequency response objectives. The cases examined suggest that for all of WECC, minimum targets of 25% and 8000MW, respectively, might be adequate. The results suggest that a portion of CAISO's frequency response could be provided by out-of-state resources without adverse performance impacts. Further investigation is warranted.

While frequency response due to high variable generation is not a crisis for California, changes to the operational procedures, markets and interconnection requirements can be made gradually to avoid frequency response concerns from becoming a problem in a future with high variable energy generation.

1. INTRODUCTION

The reliable operation of a power system depends on maintaining frequency within predetermined limits around the nominal operating frequency of 60 Hertz (Hz). Failure to maintain frequency within these limits can disrupt the operation of customers' equipment, initiate disconnection of power plant equipment, and possibly lead to wide-spread blackouts. The frequency of the interconnection is controlled by adjusting the output of generators in order to maintain the balance between generation and load. This balancing and frequency control occur over a continuum of time using different resources that fall under the category of primary, secondary or tertiary controls.

Primary frequency control, or frequency response, depends on the rapid, autonomous action of resources, particularly generation, in response to significant changes in system frequency. Primary frequency control actions are the first line of defense for the system to avoid involuntary interruption of customers, which can occur within a few seconds following a system disturbance.

Secondary frequency control is the fastest centralized control in the system. Secondary control actions are usually due to Automatic Generation Control (AGC) instructions that are issued through a Balancing Authority's Energy Management System (EMS). They start within tens of seconds, and dominate system response for the first several minutes following a disturbance.

Tertiary control encompasses dispatch actions taken by the system operator to get resources in place to handle current and future contingencies. Reserve deployment and reserve restoration following a disturbance are common types of tertiary control.

Variable energy resources, wind and solar generation in particular, presents challenges for reliable operation of the power system due to the variable nature of their generation. The CAISO has performed a detailed study [2] to evaluate the impact of higher penetration of variable energy resources on secondary control (regulation and load following) and tertiary control (unit commitment and dispatch) timeframe. The frequency response of the system, or the response of the primary control immediately following a large disturbance, is addressed in this study. Other aspects of system dynamics, including possible impact on stability constrained transfer limits, are not within the scope of this study.

This study builds on recent work sponsored by the Federal Energy Regulatory Commission (FERC), and by the Lawrence Berkeley National Lab (LBNL) [3] that identified metrics which are useful in planning and operations of a system with high amounts of variable generation. The first metric, frequency nadir, is a direct measure of how close a system has come to interrupting delivery of electricity to customers. The second metric, nadir-based frequency response, relates the amount of generation lost to the decline in frequency until arrested. The third metric, primary frequency response, measures the power actually delivered by primary frequency control actions during critical periods before and after the nadir is formed. The LBNL report focused on four major impacts that increased renewable generation will have on the primary frequency control actions:

- Lower System Inertia – Lower system inertia due to increased renewable penetration increases the rate of change of frequency immediately following disturbances, and therefore can increase the speed requirements for primary frequency control reserves. However, the study concludes that the effect of lower inertia is likely to be minor effect in establishing requirements for adequate primary frequency control.
- Displacement of primary frequency control reserves - The amount of primary frequency control reserves that are on line and available may be reduced as the conventional generation-based sources for these reserves are displaced by the economic dispatch of variable renewable generation, which currently does not provide primary frequency control.
- Location of primary frequency control reserves – The resulting re-dispatch of the resources (generation and demand response) that are expected to provide primary frequency control may lead to transmission bottlenecks that prevent effective delivery of primary frequency control when it is needed.
- Increased requirements on the adequacy of secondary frequency control reserves - The demands placed on secondary frequency control reserves will increase because of more frequent, faster, and/or longer ramps in net system load caused by variable renewable generation. If these ramps exceed the capabilities of secondary frequency control reserves, primary frequency control reserves (that are set-aside to respond to the sudden loss of conventional generators) will be used to make up for the shortfall. The remaining primary frequency control reserves may be inadequate to

prevent operation of under-frequency load shedding following the sudden loss of a large generator.

In addition to coming up with metrics, the LBNL study also simulated the frequency response of the three U.S interconnections under future wind generation scenarios. For the Western Interconnection, the wind generation scenarios were developed by adjusting the amount of wind energy produced at the locations that are already represented in the Winter 2012-13 light-load WECC case. The scenarios included 9 GW of installed wind generation capacity, which based on an assumed 35% capacity factor and NERC's estimate of electricity demand in 2012 could supply approximately 3 percent of the interconnection's expected electricity requirements in 2012. Higher levels of wind generation capacity were not studied due to the unavailability of transmission planning data. The simulation studies confirmed that the interconnection can be reliably operated with the amount of wind generation and supporting transmission expected by 2012 assuming operating reserve conditions that are representative of current practices and that are used in daily operations. However, the study also identified risks to reliability under certain operating conditions involving times of minimum system load, high levels of wind generation, and with operating reserves near the minimum that is allowable under current operating procedures and standards.

The current study examines cases with significantly higher levels of wind and solar, with instantaneous penetrations up to 50% in California, and 25% across all of WECC. In addition, this study includes investigations of various sensitivities, and impacts of measures to improve frequency response. The specific objectives of the study are discussed in Section 1.1.

1.1. STUDY OBJECTIVES

Under high renewable penetration levels, such as the 33% RPS envisioned by CAISO, it is conceivable that frequency response of the WECC system, and California's contribution to it, will be lower due to lower inertia of the system and the displacement of primary frequency control reserves. The frequency decline following a large generator trip could reach under-frequency load shedding (UFLS) thresholds if the system has insufficient amounts of frequency responsive resources available. The primary frequency response, and hence the ability of the system to ride through the fault without shedding any load, will depend on several factors. These include (a) system conditions before the fault, (b) the size of the outage, (c) the inertia of the system, (d) the headroom available on generators, and (e) the number and speed of governors providing frequency response.

New metrics may be required to accurately measure frequency response characteristics of the system, especially the contribution of a balancing area to the overall frequency response. Mitigation measures such as faster governor response, reduced withdrawal, inertial/ governor response of wind generators, fast-acting demand response and energy storage may need to be employed. However, their efficacy needs to be evaluated.

The objectives of this study were to evaluate:

- *frequency response to large generation outages for CAISO as well as the overall WECC, under a variety of system condition*s - frequency response was evaluated under a variety of spring and winter load conditions under high penetration of wind and solar generation. The response of the system to large system disturbances was evaluated using standard frequency response metrics; those developed by LBNL, as well as newly developed ones.
- *the impact of unit commitment/dispatch on frequency response* - existing de-commitment and re-dispatch procedures were used to determine the non-renewable generation mix in these cases.
- *the impact of generator output level on governor response* – particularly, the impact of the headroom or unloaded synchronized capacity of units with responsive governors and speed of governor response on the frequency response metrics. Also, the impact of the number of generators with governors and the effect of governor withdrawal on frequency response was evaluated.
- *potential mitigation measures* – efficacy of mitigation measures such as, faster governor response, reduced withdrawal, inertial controls and governor-like response of wind generators, and fast-acting demand response and energy storage.

1.2. SCOPE OF WORK AND MAJOR TASKS

The study was performed under the following tasks:

Task 1: Development of Study Database and Frequency Response Metrics

In this task, CAISO and GE jointly developed the loadflow Base Cases for the study. Four basic power flow conditions, given below, were jointly selected by CAISO and GE to represent system conditions of interest, e.g., light load and high wind generation.

"Winter Low Load – High CAISO Wind" (May 13 LW-HW case)

"Weekend Morning – High CAISO Wind and Solar" (Aug 9 case)

"Winter Off-Peak – High Wind" (April 23 LW-HW case)

"Spring Peak – High Hydro and Wind" (March 23 case)

In addition, seven frequency response metrics, as well as the outages to be studied, were identified or developed as a part of this task. The response of the system to two different outages, each involving the trip of two large generators, was evaluated using standard frequency response metrics, those developed by LBNL, as well as ones newly developed under this task.

Task 2: Frequency Response of Base Cases

In Task 2, the frequency response of CAISO, as well as overall WECC, for the four Base Cases to two large generation outages were evaluated. The performance was evaluated using the seven metrics developed in Task 1. The results of Base Cases were used as a comparison against the results for the high renewable penetration cases performed under Task 3.

Task 3: Frequency Response of High Renewable Penetration Cases

In Task 3, the CAISO, as well as overall WECC, frequency response under high renewable penetration was evaluated. Frequency response simulations under high renewable generation conditions were performed for the two Base Cases (Winter Low Load, Weekend Morning) that showed the most stressed frequency response. Only the most severe outage (i.e., Loss of two Palo Verde generators) was studied for the above two cases. The Winter Low Load case under the high renewable generation scenario had 11,000 MW from wind and solar in California, which was 37% of total generation in state. The Weekend Morning case under the high renewable generation scenario had 15,300 MW (50% of total) generation from wind and solar in California. Different methods were employed to decommit and re-dispatch generation in CAISO and WECC to account for renewable generation. The performance was evaluated using the seven metrics developed in Task 1.

Task 4: Factors Affecting Frequency Response

In this task, various factors degrading the frequency response were evaluated. The impact of reduced inertia, reduced numbers of governors providing frequency response, lower headroom, and governor withdrawal were all studied using the metrics from Task 1.

Task 5: Mitigation Measures

In Task 5, the impacts of various mitigation measures on the frequency response metrics were studied. The mitigation measures included the following: reduced governor withdrawal, faster governor response, inertial controls and governor-like response from wind generation, demand response and energy storage.

2. DEVELOPMENT OF STUDY DATABASE AND PERFORMANCE METRICS

This section discusses the development of the databases and performance metrics for this study.

2.1. OVERVIEW OF STUDY BASE CASES

The base cases selected for this study by CAISO were intended to represent a range of operating points with high levels of renewables in California, and conditions which could be challenging from a frequency response perspective.

CAISO developed these cases starting from established planning data bases (WECC base cases database), adding wind and solar generation, and changing commitment and dispatch of other generation within California according to their general expectation of CAISO operations and markets. **Table 2-1** gives a brief synopsis of the four base cases. In subsequent sections, details including load levels, generation mix, headroom, responsiveness, wind, solar, etc., for each of these cases will be presented.

Table 2-1 Study Base Cases

	WECC Load (MW)	WECC Wind Power (MW)	WECC Solar Power (MW)
Winter Low Load – High CAISO Wind	91300	13341	2550
Weekend Morning – High CAISO Wind and Solar	110798	12720	6810
Winter Off Peak – High Wind	97447	13414	2556
Spring Peak - High Hydro and Wind	140167	9904	2571

Simulation results for these base cases will be presented in Section 3, and cases with additional wind in the rest of WECC will be presented in Section 4. But before we present the details of the individual cases, we will explain the performance metrics being reported for each case. This will provide context for some of the specifics for each case that are highlighted.

2.2. PERFORMANCE METRICS

Several performance metrics are reported for each case. The following list of descriptions is keyed to notations in ***Figure 2-1***.

- **Frequency Nadir.** This is point C_f in the figure. Notice that, since the frequency of all of WECC and California are subtly different, the amplitude of the nadir is very slightly different between the two. This is discussed in the next subsection.
- **Frequency Nadir Time.** This is point C_t in the figure – the time it takes for the response to reach its nadir.
- **LBNL Nadir-based Frequency Response.** This metric is much like the NERC Frequency Response metric, but it is measured at the frequency nadir. It is defined as the size of the disturbance - e.g. 2690MW in the case of the loss of two Palo Verde units) divided by change in frequency to the nadir, and then normalized to units of MW/0.1Hz (i.e. the quotient is multiplied by 0.1). In this sense, it is a system-wide metric, in that frequency at the nadir is *similar, but not identical,* everywhere in the system. Measurement and calculation of frequency, especially during the early stages of a large disturbance is not simple. A discussion of how frequency was calculated for this study is provided in Section 2.2.1.
- **GE-CAISO Nadir-based Frequency Response.** This metric is new in that it assigns the contribution of governors (and other actively participating resources) to the overall system response at the nadir by entity. The metric is the change in MW output by all the active governors in the entity (See range C_P in the figure) *at the time of the frequency nadir,* divided by the change in frequency to the nadir. Like the other performance metrics, it is normalized to MW/0.1Hz.
- **Settling Frequency**. For results presented throughout this report, this is defined as the frequency at 60 seconds, see point B_f in the figure. The intent of this metric is to capture the frequency after the autonomous controls (mainly governors) have acted, but before centralized control (mainly AGC) acts. In practice, these behaviors overlap, and so it is difficult to assign a

specific post disturbance time to make a single measurement. The NERC frequency response obligation (FRO) proposes [1,4] the use of an average over a period after the nadir (e.g. 20 to 52 seconds) for calculating the settling frequency. Different windows are under consideration. However, since the simulations performed in this study do not include representation of AGC, testing the system frequency at the end of the 1-minute simulation best meets the intent of the first part of the metric. The final definition adopted by NERC for this metric will have some quantitative impact on the performance metrics reported here.

- **NERC Frequency Response**. For this study, we have calculated NERC Frequency Response as the ratio of the size of the event (e.g. 2690MW) to the settling frequency, which we measure at 60 seconds. This gives a broad measure of the total impact of governor response, load response, changes in losses, etc. It is essentially the same across the entire system, with the fact that very slight differences in frequency will persist even 60 seconds after the disturbance.

- **GE-CAISO Settling-based Frequency Response**. This metric assigns the contribution of governors (and other actively participating resources) to the overall system frequency response by entity. The metric is the change in MW output by all the active governors in the entity (see range BP in the figure), group divided by the change in frequency to the settling frequency (point B). The intent is to capture the "share" of each entity's contribution to frequency response. This measurement is meant to be reflective of the intent of the NERC FRO.

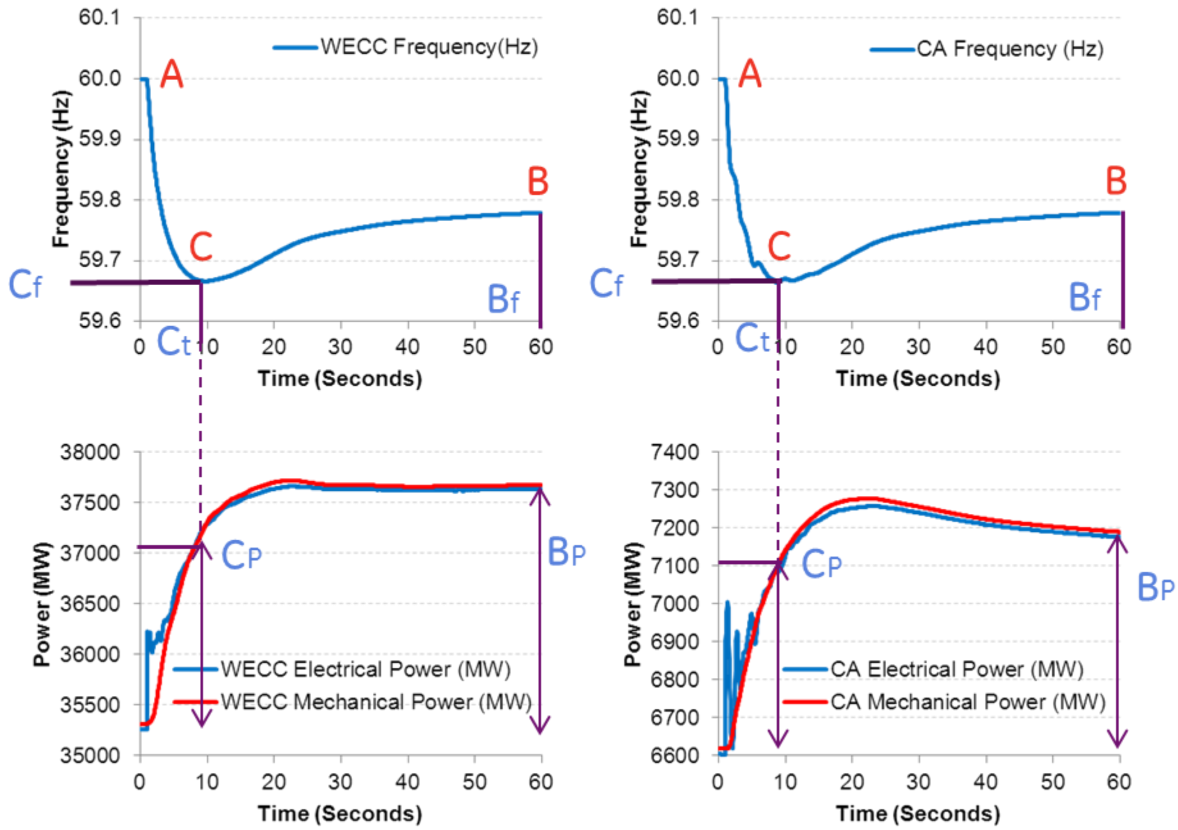

Figure 2-1 Description of Performance Metrics

2.2.1. FREQUENCY CALCULATION

This study is focused on broad systemic issues of frequency response. Measuring the frequency at a specific single node in the grid following a disturbance can be confusing and misleading. A system equivalent frequency, *f*, has been introduced, which can be calculated as

$$f = \frac{\sum_{i=1}^{n}(MVA_i * \omega_i)}{\sum_{i=1}^{n} MVA_i} \qquad (2.1)$$

Where

MVA_i is the MVA rating for machine i

ω_i is the speed for machine i

n is the number of synchronous machine in the system

This is the center of inertia speed of synchronous machines in the system. It filters out the local swings to give a clearer measure of the system performance of concern in this study. It can be regarded analytically as the common mode of the system. Three system equivalent frequencies (WECC, California and Non-California) were calculated in this study.

2.3. DISPATCH AND COMMITMENT CHARACTERIZATION

The frequency response of the system is dominated by the amount and type of generation committed and how it is dispatched. Throughout the report, five distinct classes of generation are identified, in accordance with their frequency response behavior. According to the power flow and dynamic data, each of the generators in the study system can be characterized as one of the following types:

- Governor Responsive (GR)
- Base Load (BL)
- No Governor (NG)
- Wind
- Solar Photovoltaic (Solar Thermal generators are usually Governor Responsive units)

"Governor Responsive" units have governor models and will provide frequency response. "Base Load" and "No Governor" units will not provide frequency response. More specifically, "Base load" units have governors blocked from *increasing* mechanical power, but can respond to over-frequencies. Units with no governor models, will be unresponsive regardless of the sign of the frequency deviation. "Governor Response" units, "Base Load" units and "No Governor" units are also considered as "Conventional Units (CU)" in this study.

2.3.1. METRICS CHARACTERIZING DISPATCH AND COMMITMENT

Throughout the balance of the report, tables are provided that summarize important aspects of the initial conditions used for various cases. These tables are intended to capture the critical characteristics of the generation and load, as they relate to frequency performance. ***Table 2-2 Key to Case Summary Metrics*** shows a list of the reported metrics, with a brief explanation.

Table 2-2 Key to Case Summary Metrics

GR Pgen (MW)	Power generation of units with governor response
GR MWCAP (MW)	Power generation capability of units with governor response
GR Headroom (MW)	Headroom of units with governor response
BL Pgen (MW)	Power generation of units base loaded
NG Pgen (MW)	Power generation of units without governor
Wind Pgen (MW)	Power generation of wind
Solar Pgen (MW)	Power generation of solar
MW Capability = GR MWCAP + BL Pgen + NG Pgen + Wind Pgen + Solar Pgen	MW capability of all online generation units
CU Pgen (MW) (GR + BL + NG)	Power generation of conventional units
Total Pgen (MW)	System generation
Total Pload (MW)	System load
Wind Pgen/Total Pgen	Ratio of wind power to system generation
Solar Pgen/Total Pgen	Ratio of solar power to system generation
Kt = GR MWCAP/(GR MWCAP + BL Pgen + NG Pgen + Wind Pgen + Solar Pgen)	See notes below
GR Pgen/CU Pgen	Ratio of power generation of units with governor response to power generation of conventional units
GR Pgen/Total Pgen	Ratio of power generation of units with governor response to total system generation
GR Headroom/CU Pgen	Ratio of Headroom of units with governor response to power generation of conventional units
GR Headroom/Total Pgen	Ratio of Headroom of units with governor response to total system generation

The ratio between governor response (GR) and other conventional units is used to quantify overall system readiness to provide frequency response. John Undrill, in the LBNL report [5], introduces a metric, Kt, that is this ratio. The lower Kt, the smaller the fraction of generation that will respond. The exact definition of Kt is not standardized. For this report, this is a parameter that is reported in each of the case summaries as “GR MWCAP/(GR MCAP+BL Pgen+NG Pgen+Wind Pgen+Solar Pgen)”. This is the ratio of power generation capability of units with governor response to the MW capability of all generation units. We have defined MW capability to be equal to the MW dispatch, rather than the nameplate rating of non-responsive generation, since these units will not contribute beyond their initial dispatch. We believe this is a reasonable definition, but some industry discussion of exact definition of Kt is warranted.

2.4. DETAILS OF STUDY BASE CASES

2.4.1. WINTER LOW-LOAD, HIGH-CAISO-WIND BASE CASE

This case was created by the CAISO to test response during low load conditions when there is substantial wind generation. This was intended to be a relatively extreme case for the state of California, when instantaneous penetration of wind could be quite high. The starting case for the Winter Low Load – High CAISO Wind case was the WECC 2012 Light Winter base case which simulates light load conditions. New renewable generation in the CAISO territory was added to the case according to the CAISO Generation Interconnection Queue. It was assumed that the Once-Through-Cooling (OTC) generation units in California, such as all units at Encina in San Diego, Huntington Beach, El Segundo, Mandalay Bay, Ormond Beach and Redondo Beach in Southern California, Haynes in Los Angeles and Moss Landing and Contra Costa in PG&E were retired, as well as units 5 and 6 of the Pittsburg power plant in PG&E. This generation was replaced by new renewable projects, mainly wind and solar photovoltaic. Wind generation was also modeled as running at full output in other areas of WECC, mainly the Northwest. Only approved transmission upgrades associated with the new generation projects in California were modeled. In addition, transmission projects that were included in the 2010-2011 CAISO Transmission Plan were also modeled in the case.

2.4.1.1. CASE SUMMARY

The generation information for Winter Low Load – High CAISO Wind Base Case is summarized in Table 2-3.

Table 2-3 Generation Summary for Winter Low Load – High CAISO Wind Base Case

	WECC		CA		Non-CA	
		# of Units		# of Units		# of Units
GR Pgen (MW)	35253	513	6602	122	28652	391
GR MWCAP (MW)	48993		10576		38417	
GR Headroom (MW)	13740		3974		9765	
BL Pgen (MW)	32085	319	11223	138	20862	181
NG Pgen (MW)	10849	332	2617	99	8232	233
Wind Pgen (MW)	13341		8411		4930	
Solar Pgen (MW)	2550		2550		0	
MW Capability	107818		35377		72441	
CU Pgen (MW) (GR + BL + NG)	78187	1164	20442	359	57746	805
Total Pgen (MW)	94392		29683		64710	
Total Pload (MW)	91300		26190		65111	
Wind Pgen/Total Pgen	14.1%		28.3%		7.6%	
Solar Pgen/Total Pgen	2.7%		8.6%		0.0%	
Kt	45.4%		29.9%		53.0%	
GR Pgen/CU Pgen	45.1%	44.1%	32.3%	34.0%	49.6%	48.6%
GR Pgen/Total Pgen	37.3%		22.2%		44.3%	
GR Headroom/CU Pgen	17.6%		19.4%		16.9%	
GR Headroom/Total Pgen	14.6%		13.4%		15.1%	

Notes: GR = Governor Response; BL = Base Loaded; NG = No governor; CU = Conventional Units

The WECC generation is summarized in column two and three of Table 2-3, the California generation is summarized in column four and five, and the Non-California generation is summarized in column six and seven. Note that California numbers are deliberately all of California, not just CAISO. In the columns "# of units", we have simply counted how many generators of each of the three types are committed in the case. The entry in those columns corresponding to Kt is ratio of the count of governor responsive units to the count of all conventional generators, expressed in percentage. Typically, this ratio is quite close to the MW ratio reported in the adjacent column.

In ***Table 2-4*** additional details of the type and distribution of wind and solar generation are presented. The entries TP1, TP2, etc., refer to IEEE wind generation model types. Most solar photovoltaic generation is modeled with type 4, full converter models with models of generators and inverters. The last row of the table gives the instantaneous penetration as a fraction of total generation for wind and solar. At 37% (28.3 + 8.6), the penetration in California is substantial.

Table 2-4 Wind and Solar Power Summary for Winter Low Load – High CAISO Wind Case

	WECC	CA	Non-CA
TOTAL Pgen	94392	29683	64710
TOTAL Pload	91300	26190	65111

WIND&SOLAR (MW)

	WECC		CA		Non-CA	
TP 1	2494(wind)	398(solar)	2160(wind)	398(solar)	334(wind)	0(solar)
TP 2	444(wind)		444(wind)		0(wind)	
TP 3	9809(wind)		5213(wind)		4597(wind)	
TP 4	594(wind)	1738(solar)	594(wind)	1738(solar)	0(wind)	0(solar)
epcgen		414(solar)		414(solar)		0(solar)
Total	13341(wind)	2550(solar)	8411(wind)	2550(solar)	4930(wind)	0(solar)
W&S/Pgen	14.1%(wind)	2.7%(solar)	28.3%(wind)	8.6%(solar)	7.6%(wind)	0.0%(solar)

2.4.2. WEEKEND MORNING, HIGH-CAISO-WIND-AND-SOLAR BASE CASE

This case was created by the CAISO to test response during relatively low load conditions when there is substantial solar as well as wind generation. The specific concern here is that on weekends, the system tends to de-commit a significant amount of California's flexible generation fleet. With the credible condition of high solar in the morning before wind tends to decline, the instantaneous penetration of wind and solar could be quite high.

The Weekend Morning case had higher load than the winter off-peak case to represent the conditions that may occur in spring. The starting base case for this model was WECC 2018 Heavy Spring case from the WECC database. The load was modified to reflect operating conditions during weekend mornings. The amount of load for each area and substation was derived from the CAISO market production simulation study for the year 2020. The load and generation dispatch from the production simulation model for April 4, at 11 a.m. were used to develop the base case. Similar to the Winter Low Load case, new renewable projects from the CAISO Generation Interconnection Queue, associated transmission upgrades and the transmission projects from the 2010-2011 CAISO Transmission Plan were added to the model. The OTC generation units described in the previous section were also modeled as retired.

2.4.2.1. CASE SUMMARY

The case summary is shown in ***Table 2-5*** below. The penetration of wind and solar generation in California is 50% (28.3% + 21.8%)

Table 2-5 Generation Summary for Weekend Morning – High CAISO Wind and Solar Base Case

	WECC		CA		Non-CA	
		# of Units		# of Units		# of Units
GR Pgen (MW)	48529	808	5514	127	43015	681
GR MWCAP (MW)	65984		9785		56199	
GR Headroom (MW)	17455		4271		13184	
BL Pgen (MW)	35116	381	9477	155	25639	226
NG Pgen (MW)	10972	460	1757	121	9215	339
Wind Pgen (MW)	12720		8645		3386	
Solar Pgen (MW)	6810		6666		144	
MW Capability	131602		36330		94583	
CU Pgen (MW) (GR + BL + NG)	94617	1649	16748	403	77869	1246
Total Pgen (MW)	114775		30525		84250	
Total Load (MW)	110798		35155		75643	
Wind Pgen/Total Pgen	11.1%		28.3%		4.0%	
Solar Pgen/Total Pgen	5.9%		21.8%		0.2%	
Kt	50.1%		26.9%		59.4%	
GR Pgen/CU Pgen	51.3%	49.0%	32.9%	31.5%	55.2%	54.7%
GR Pgen/Total Pgen	42.3%		18.1%		51.1%	
GR Headroom/CU Pgen	18.4%		25.5%		16.9%	
GR Headroom/Total Pgen	15.2%		14.0%		15.6%	

2.4.3. WINTER OFF-PEAK, HIGH-WIND BASE CASE

This case was created by CAISO to evaluate frequency response during relatively low load conditions in the winter, when a significant amount of California's flexible generation fleet would tend to be off-line. This condition results in fewer units committed. Some of the de-committed units would normally contribute to frequency response. The difference between this case and the Winter Low load case was that the load in this case was slightly higher, and the wind generation was also higher. The model for this case was derived from the ISO's Production simulation for the year 2020, and the loads for all areas in the power flow case were modified according to the ISO's production simulation input data. The date and hour selected to study was February 24, 3 a.m. The starting base case was 2016 Light Autumn base case from the WECC database because this case better represented the load for the selected date and hour observed in the production simulation. Similar to the previous cases, the renewable generation from the CAISO Generation Interconnection queue and appropriate transmission upgrades were added to the power flow case. The renewable generation was dispatched higher than in the Winter Low Load case. OTC generation in California was also modeled as retired. Compared to the Winter Low load case, this case has 2,800 MW of additional wind generation dispatched in the Pacific Northwest.

2.4.3.1. CASE SUMMARY

The case summary sheet is shown in ***Table 2-6***. This case has 41% wind and solar (31.6% + 9.6%) penetration in California. This higher penetration compared to the Winter Low Load – High CAISO Wind Base Case is because of the higher imports and less non-wind and non-solar generation dispatched within the state.

Table 2-6 Generation Summary for Winter Off Peak – High Wind Base Case

	WECC		CA		Non-CA	
		# of Units		# of Units		# of Units
GR Pgen (MW)	37745	583	6028	140	31717	443
GR MWCAP (MW)	53154		11343		41811	
GR Headroom (MW)	15409		5315		10094	
BL Pgen (MW)	33986	350	8889	142	25097	208
NG Pgen (MW)	12953	391	2518	138	10434	253
Wind Pgen (MW)	13414		8433		4981	
Solar Pgen (MW)	2556		2556		0	
MW Capability	116063		33739		82323	
CU Pgen (MW) (GR + BL + NG)	84684	1324	17435	420	67248	904
Total Pgen (MW)	101080		26706		74374	
Total Load (MW)	97447		27873		69574	
Wind Pgen/Total Pgen	13.3%		31.6%		6.7%	
Solar Pgen/Total Pgen	2.5%		9.6%		0.0%	
Kt	45.8%		33.6%		50.8%	
GR Pgen/CU Pgen	44.6%	44.0%	34.6%	33.3%	47.2%	49.0%
GR Pgen/Total Pgen	37.3%		22.6%		42.6%	
GR Headroom/CU Pgen	18.2%		30.5%		15.0%	
GR Headroom/Total Pgen	15.2%		19.9%		13.6%	

2.4.4. SPRING PEAK – HIGH HYDRO AND WIND BASE CASE

This case was created by CAISO to test response during high hydro conditions. This condition results in a substantial amount of California hydro being run flat-out, such that it has little or no headroom and tends to displace other thermal generation on the system which might otherwise contribute to frequency response. The starting case for these conditions was the 2018 Heavy Spring case from the WECC database. The system load in this case was higher than in the weekend morning case, wind and solar PV generation was lower, and hydro generation in California was high. As in all other cases, renewable projects from the CAISO Generation Interconnection Queue and transmission upgrades were added to the system model. OTC units were also modeled as retired.

2.4.4.1. CASE SUMMARY

The case summary in is provided in ***Table 2-7***. The instantaneous penetration of wind and solar PV in this case is 32% (24.6% + 7.5%). At 32%, the Kt is relatively high, as the generation mix for this case results in a high level of governor participation, hydro generation base loaded notwithstanding.

Table 2-7 Generation Summary for Spring Peak - High Hydro and Wind Base Case

	WECC		CA		Non-CA	
		# of Units		# of Units		# of Units
GR Pgen (MW)	65449	909	9736	163	55713	746
GR MWCAP (MW)	83655		13744		69911	
GR Headroom (MW)	18206	460	4008	186	14198	274
BL Pgen (MW)	47160	510	12091	154	35070	356
NG Pgen (MW)	19660		2939		16722	
Wind Pgen (MW)	9904		8427		1477	
Solar Pgen (MW)	2571		2571		0	
MW Capability	162950		39772		123180	
CU Pgen (MW) (GR + BL + NG)	132269	1419	24766	317	107505	1102
Total Pgen (MW)	145222		34188		111034	
Total Load (MW)	140167		44697		95470	
Wind Pgen/Total Pgen	6.8%		24.6%		1.3%	
Solar Pgen/Total Pgen	1.8%		7.5%		0.0%	
Kt	51.3%		34.6%		56.8%	
GR Pgen/CU Pgen	49.5%	64.1%	39.3%	51.4%	51.8%	67.7%
GR Pgen/Total Pgen	45.1%		28.5%		50.2%	
GR Headroom/CU Pgen	13.8%		16.2%		13.2%	
GR Headroom/Total Pgen	12.5%		11.7%		12.8%	

2.5. GENERATION TRIP EVENTS

Two critical generation trip events, one inside California and one outside California, were evaluated in this study. The two events are shown in Table 2-8.

Table 2-8 Generator Trip Events

Loss of Two Palo Verde units: (2690-2812 MW tripped)33	Outside California
Loss of Two Diablo Canyon units (2400 MW tripped)	Inside California

3. FREQUENCY RESPONSE OF BASE CASES

The frequency response of the four base cases are discussed in sections 3.1 through 3.4 respectively. Section 3.5 discusses the governor response in these cases. While most of the simulations were performed for an outage of two Palo Verde units, simulations were also performed for the loss of a single Palo Verde unit. The results from this simulations are discussed in Section 3.6.

3.1. WINTER LOW LOAD – HIGH CAISO WIND BASE CASE

The results for the Winter Low Load – High CAISO Wind Base Case are discussed here.

3.1.1. RESPONSE TO PALO VERDE DISTURBANCE

The top row of plots of ***Figure 3-1*** shows the frequency response to loss of two Palo Verde Units for the Winter Low Load – High CAISO Wind Base Case. For WECC, the nadir of frequency occurs at 9.8 seconds at a frequency of 59.67 Hz and the settling frequency is 59.78 Hz. For California, the nadir of frequency occurs at 8.7 seconds at a frequency of 59.66 Hz and the settling frequency is 59.78 Hz. For Non-California, the nadir of frequency occurs at 9.9 seconds at a frequency of 59.69 Hz and the settling frequency is 59.78 Hz. The slight difference in the frequency values are discussed in Section 2.2.1.

The bottom row of plots of ***Figure 3-1*** shows the electrical and mechanical power output of Governor Response units to loss of two Palo Verde Units for the Winter Low Load – High CAISO Wind Base Case. As expected, by 60 seconds, the inter-area transients have settled out, frequency is largely uniform everywhere, and generator electrical and mechanical power are essentially equal. The change in generation by governor responsive units represents the vast majority of system response and is nearly equal to the lost generation (2690 MW).

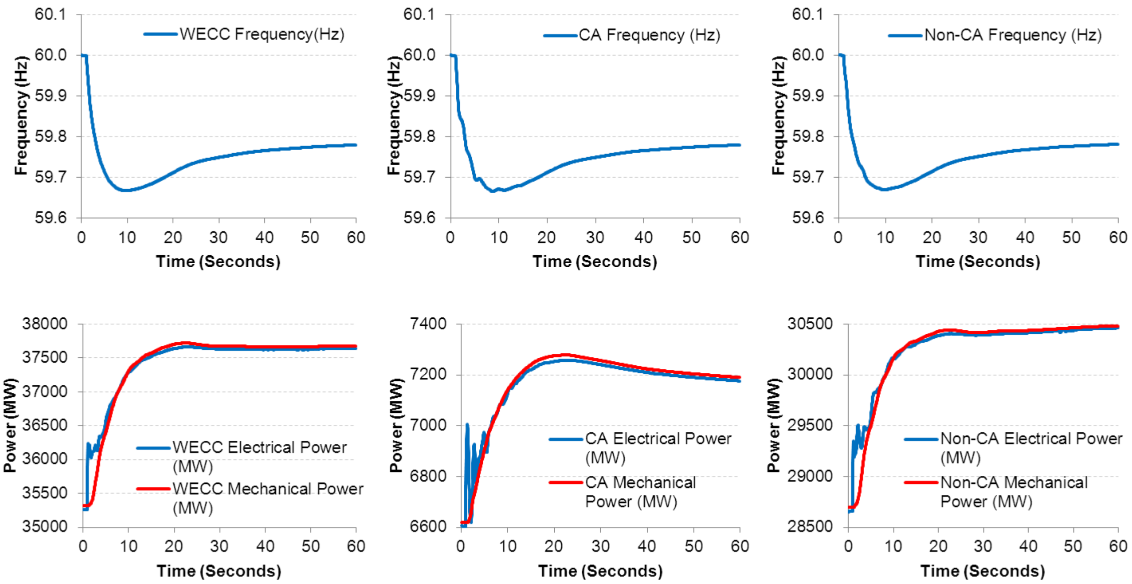

Figure 3-1 Frequency and Governor Response to Loss of Two Palo Verde Units

3.1.1.1. PERFORMANCE SUMMARY

The performance metrics for this case are presented in ***Table 3-1***.

Table 3-1 Performance Metrics for the Loss of Two Palo Verde Units – Winter Low Load – High CAISO Wind Base Case

	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.67	59.66	59.67
Frequency Nadir Time (Seconds)	9.8	8.7	9.9
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	806	801	810
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	641	154	479
Percent of Total (%)		24.0	74.7
Settling Frequency (Hz)	59.78	59.78	59.78
NERC Frequency Response (MW/0.1Hz)	1218	1217	1226
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	968	234	726
Percent of Total (%)		24.2	75.0

The frequency nadir of 59.67 Hz for this case gives about 170 mHz margin above first stage under-frequency load shedding at 59.5 Hz. Accounting for a steady-state frequency uncertainty of 50mHz, this represents about 120 mHz of margin. Since the Palo Verde event is nominally the most extreme design basis event for frequency variation in WECC, this margin more than adequate to meet present NERC expectations.

The time to the frequency nadir of about 9 seconds is typical of large, mixed resource systems. More severe events, with deeper nadirs, tend take longer to reach the minimum and to recover.

The LNBL nadir-based frequency response for this case is around 800 MW. Since this case avoids under frequency load shedding by a reasonable margin, this level of response seems adequate.

The GE-CAISO nadir metric is 641 MW for all of WECC, with 24% of that coming from California generators. Since this metric only reflects governor (and other active resources), it is smaller than the LBNL metric (806 MW). For this specific condition, California load (26190 MW) is 29 % of the total (91300 MW), and California generation (29683 MW) is 31% of the total (94392 MW).

The settling frequency is 59.78Hz, with differences lost in round-off between the 3 measures. Small differences are visible between the NERC frequency response numbers. The total response, 1218 MW/0.1Hz is greater than 1% of the system load in this case, but less than 1% of peak WECC load. Since the system avoids UFLS with reasonable margin, this level of response may be adequate.

Again, the GE-CAISO Settling-based Frequency Response metric, which only considers active (governor) response is smaller at 968 MW/0.1Hz. The fraction that California contributes is again about 24% at 234MW/0.1Hz. The proposed "base obligation" [1] for the Western system is 548MW/0.1Hz, and 685MW/0.1 for a 25% safety margin. If California were assigned 30% of this obligation, the CA obligation with margin would be 205 MW/0.1Hz. So, in this case, California appears to comfortably meet the proposed FRO.

The sum of the California and non-California metrics are close to, but not identical, to the all WECC metrics. This is because of the differences in frequency calculation.

3.1.1.2. FREQUENCY BEHAVIOR

Figure 3-2 shows the system frequency behavior for the Winter Low Load – High CAISO Wind Base Case for system frequencies and a number of buses. The plots in the first column show the WECC frequency and three selected 500 kV bus frequencies. Plots in the second column show the California frequency and three selected California 500 kV bus frequencies. Plots in the last column show the Non-California frequency and three Non-California 500 kV bus frequencies. Notice that only the WECC curves in ***Figure 3-2*** are smooth, as anticipated above in section 2.2.

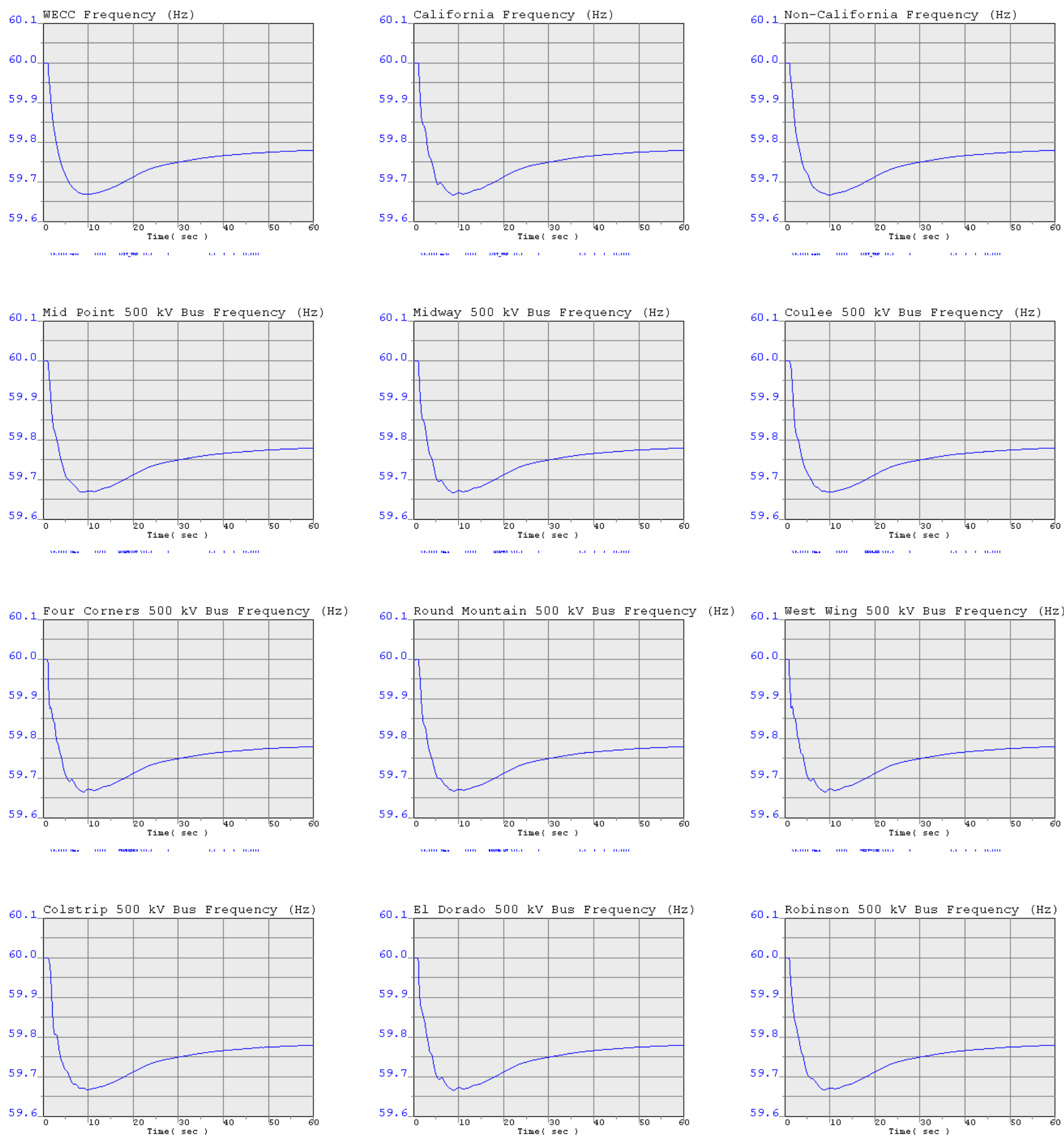

Figure 3-2 Frequency Behavior to Loss of Two Palo Verde Units for Winter Low Load – High CAISO Wind Base Case

3.1.1.3. GOVERNOR RESPONSE

Figure 3-3 shows the electric power and mechanical power (governor response) of selected machines in WECC. There is a range of responses, including no governor response for baseload units like Colstrip, San Juan and Castaic PSH (Pmech is not shown for Castaic).

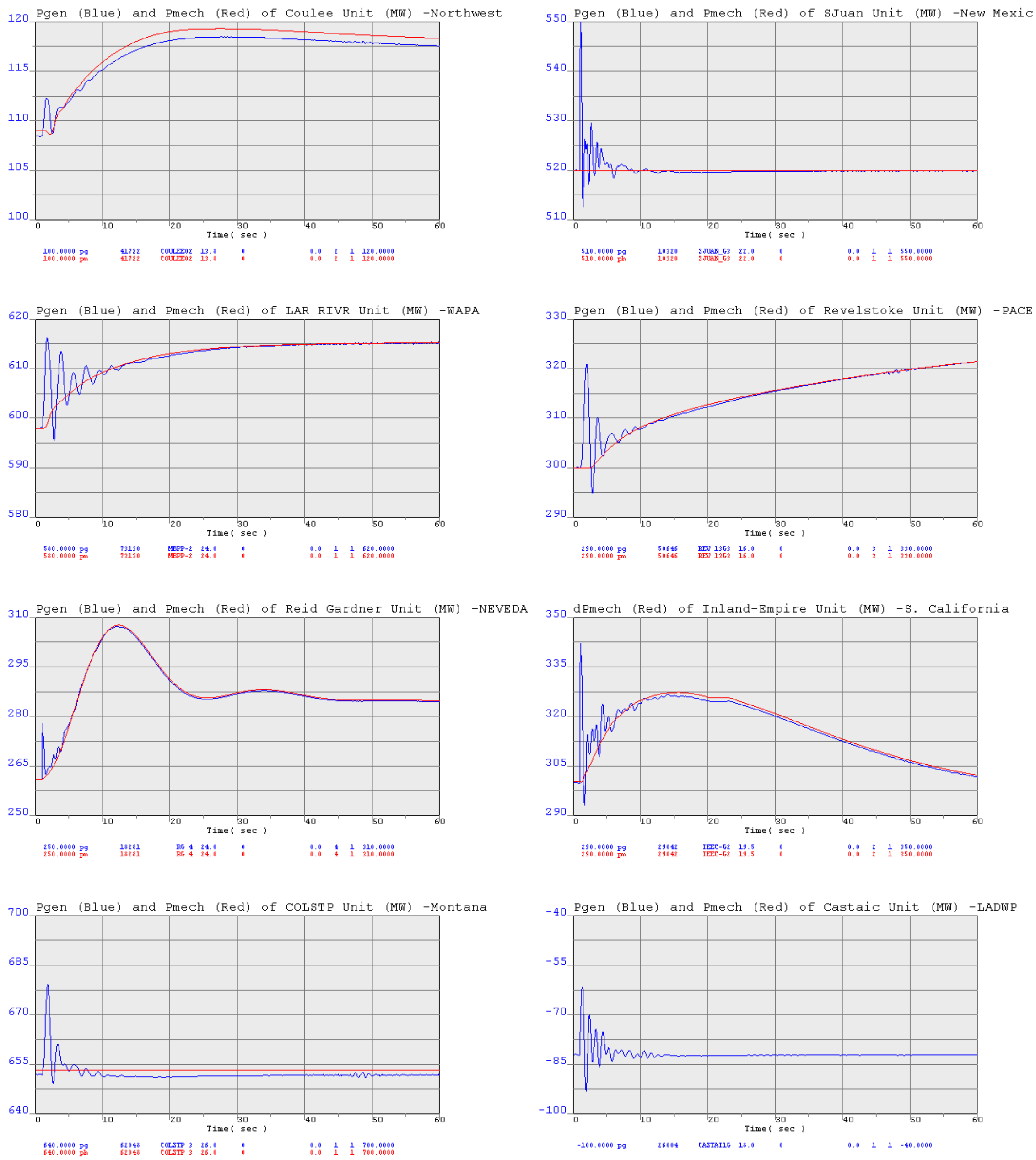

Figure 3-3 Governor Response to Loss of Two Palo Verde Units for Winter Low Load – High CAISO Wind Base Case

3.1.1.4. GRID FLOWS

Key interface flows for this case are shown in ***Figure 3-4***. Of these various major interface flows, the increase of flow over the California-Oregon Interface (COI) is of particular interest. Loss of 2 Palo Verde units results in a massive redistribution of power production and an increase of north to south flow on COI, as system angles rapidly change due to the loss of the power injection from Palo Verde. Under this winter condition, flow is initially south to north, so this event results in unloading of the interface. Other times, when California is importing power from the northwest, this event will result in increased stress on COI. Unsurprisingly, loss of Palo Verde units results in a large drop in flows towards California.

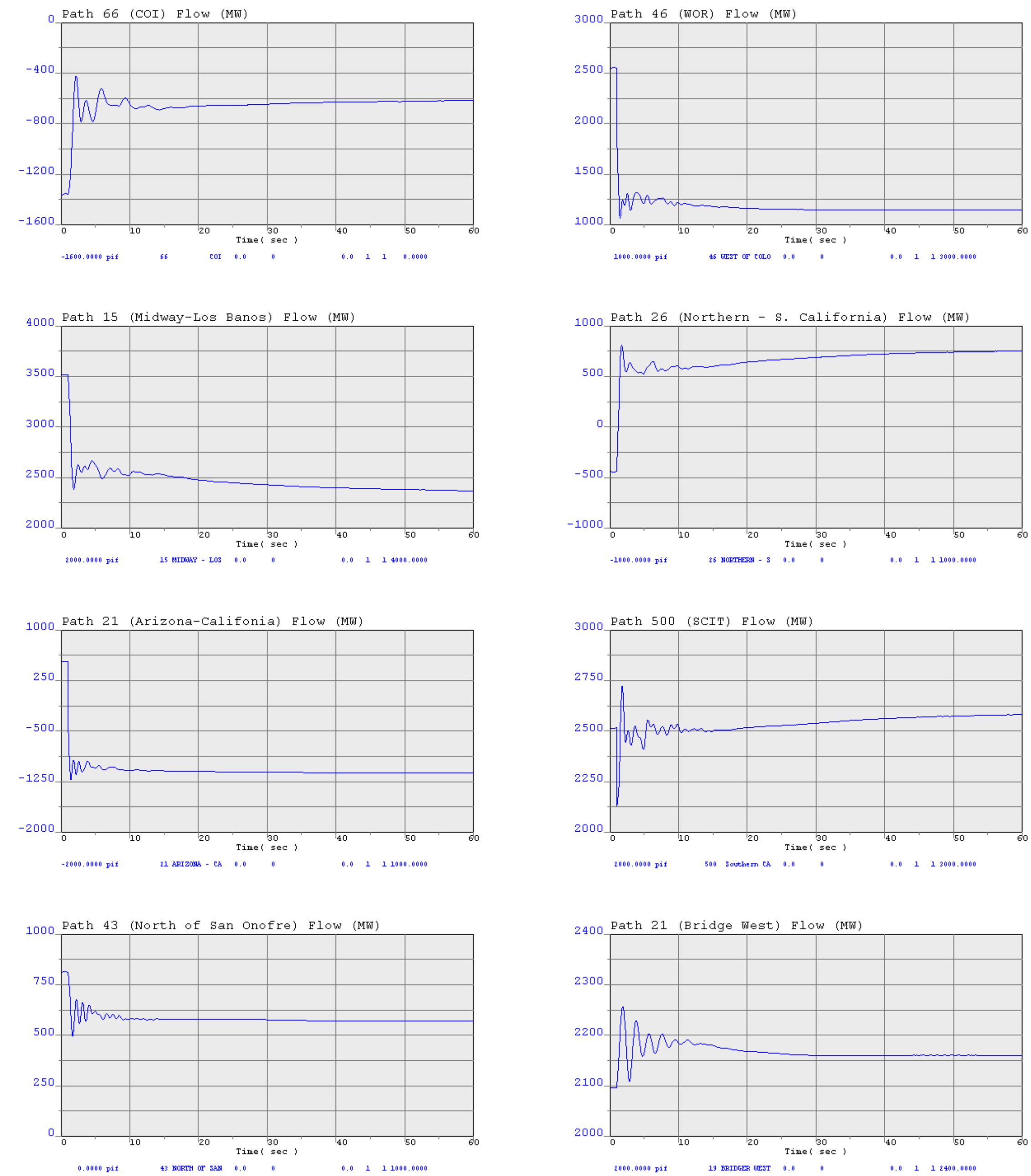

Figure 3-4 Interface Power Flow Response to Loss of Two Palo Verde Units for Winter Low Load – High CAISO Wind Base Case

3.1.2. RESPONSE TO DIABLO CANYON EVENT

Figure 3-5 shows the system response to the loss of two Diablo Canyon units (2400 MW). The nadir of WECC frequency occurs at 9.63 seconds at a frequency of 59.71 Hz. The nadir of California frequency occurs at 8.85 seconds at a frequency of 59.71 Hz. The frequency deviation is less severe than those for the loss of two Palo Verde units event (2690 MW). Since we are solely concerned with frequency response in this study, the rest of this report focuses on investigating the system response to the loss of two Palo Verde units. Under some conditions, it is possible that the Diablo Canyon event presents a more difficult stability problem.

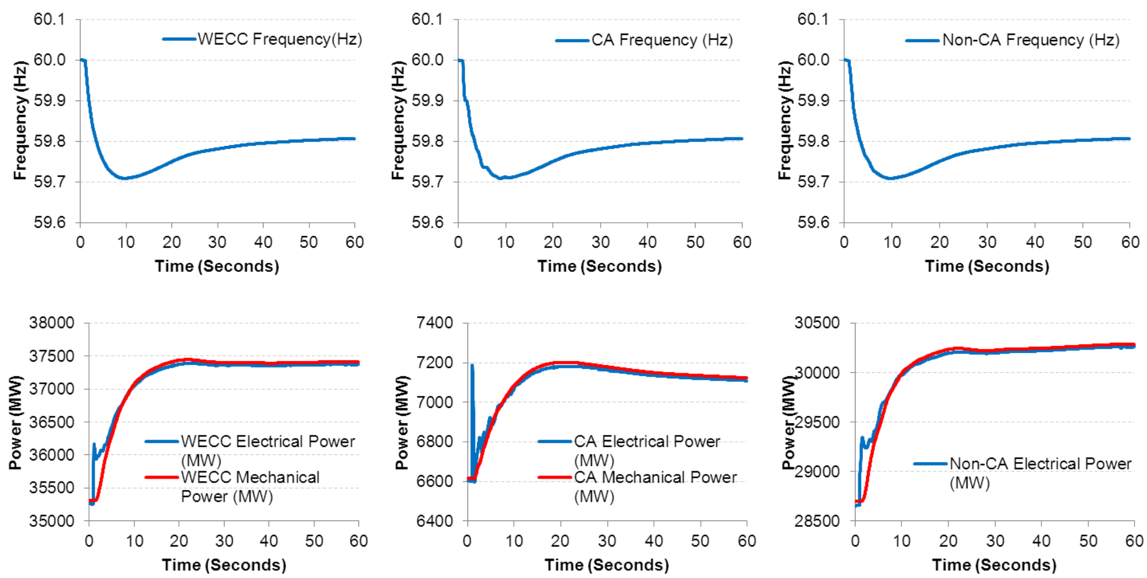

Figure 3-5 Frequency and Governor Response to Loss of Two Diablo Canyon Units

3.2. WEEKEND MORNING – HIGH CAISO WIND AND SOLAR

The results for the Weekend Morning – High CAISO Wind and Solar Base Case are discussed here.

3.2.1. RESPONSE TO PALO VERDE DISTURBANCE

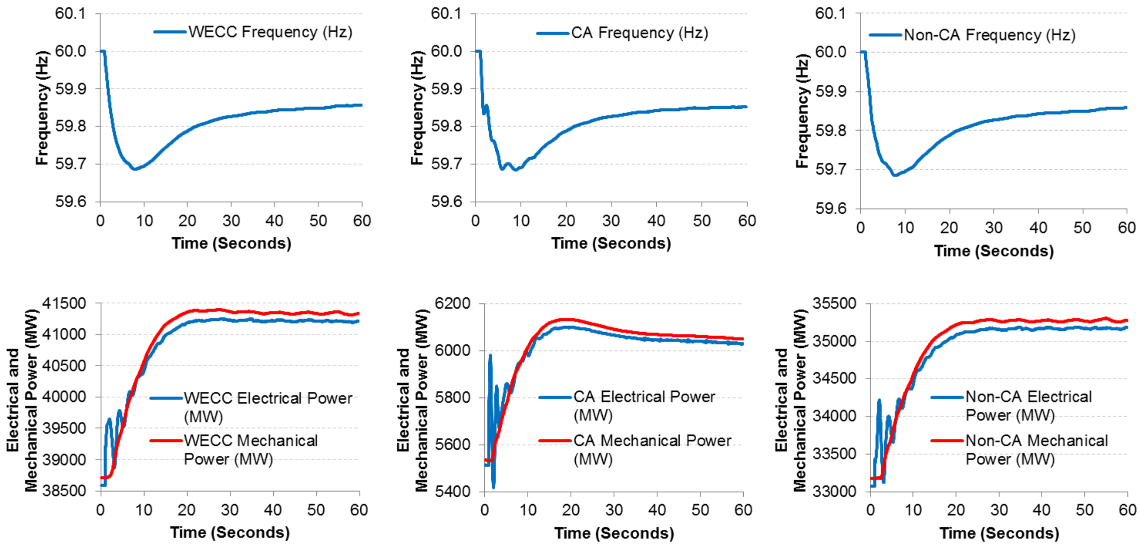

Figure 3-6 Frequency and Governor Response to Loss of Two Palo Verde Units

The performance of this case, as expected, is similar to the Wind low load – High CAISO wind case. Since the Kt and headroom are slightly higher across all of WECC (even though Kt for California is a little lower (30% vs. 27% - from the case summary tables), the frequency nadir of 59.69 gives a slightly higher margin of 190mHz of above UFLS, including initial frequency uncertainty. Thus, even though this case has significantly higher instantaneous penetration of wind and solar in California (50% vs. 37% for the winter case), the overall performance is consistent with Kt and headroom. The GE-CAISO response of 286 MW/0.1Hz is comfortably above the proposed target of 205 MW/0.1Hz. Instantaneous penetration of wind and solar power alone does not appear to be a good metric of expected frequency performance.

Table 3-2 Performance Metrics for Weekend Morning – High CAISO Wind and Solar Case

	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.69	59.68	59.68
Frequency Nadir Time (Seconds)	8.0	8.8	7.8
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	858	852	853
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	658	134	503
Percent of Total (%)		20.0	76.0
Settling Frequency (Hz)	59.86	59.85	59.86
NERC Frequency Response (MW/0.1Hz)	1878	1824	1893
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	1440	287	1116
Percent of Total (%)		20.0	78.0

3.3. WINTER OFF-PEAK – HIGH WIND BASE CASE

The results for the Winter Off-Peak – High Wind Base Case are discussed here.

3.3.1. RESPONSE TO PALO VERDE DISTURBANCE

This case is similar to the Wind Low Load – High Wind base case presented above, but with slightly higher loads and higher imports. The performance is also similar, but slightly better, so subsequent investigations focused on the low load, rather than the off-peak load case.

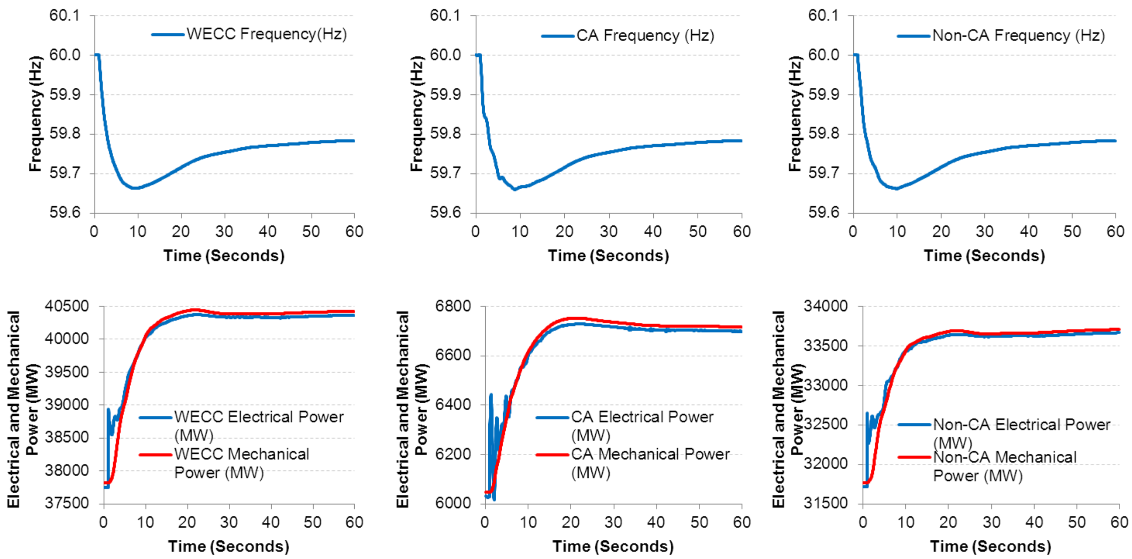

Figure 3-7 Frequency and Governor Response to Loss of Two Palo Verde Units

Table 3-3 Performance Metrics for Winter Off-Peak – High Wind Base Case

	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.67	59.66	59.67
Frequency Nadir Time (Seconds)	9.7	8.8	9.9
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	797	790	795
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	671	165	501
Percent of Total (%)		24.6	74.7
Settling Frequency (Hz)	59.78	59.78	59.78
NERC Frequency Response (MW/0.1Hz)	1242	1241	1242
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	1045	260	782
Percent of Total (%)		24.9	74.8

3.4. SPRING PEAK – HIGH HYDRO AND WIND BASE CASE

The results for the Spring Peak – High Hydro and Wind Base Case are discussed here.

3.4.1. RESPONSE TO PALO VERDE DISTURBANCE

The performance of this case, shown in ***Figure 3-8***, is substantially better than the preceding three. The margin above UFLS is greater than 250 mHz. This suggests that high hydro generation is not, in itself, indicative of risk of poor frequency response.

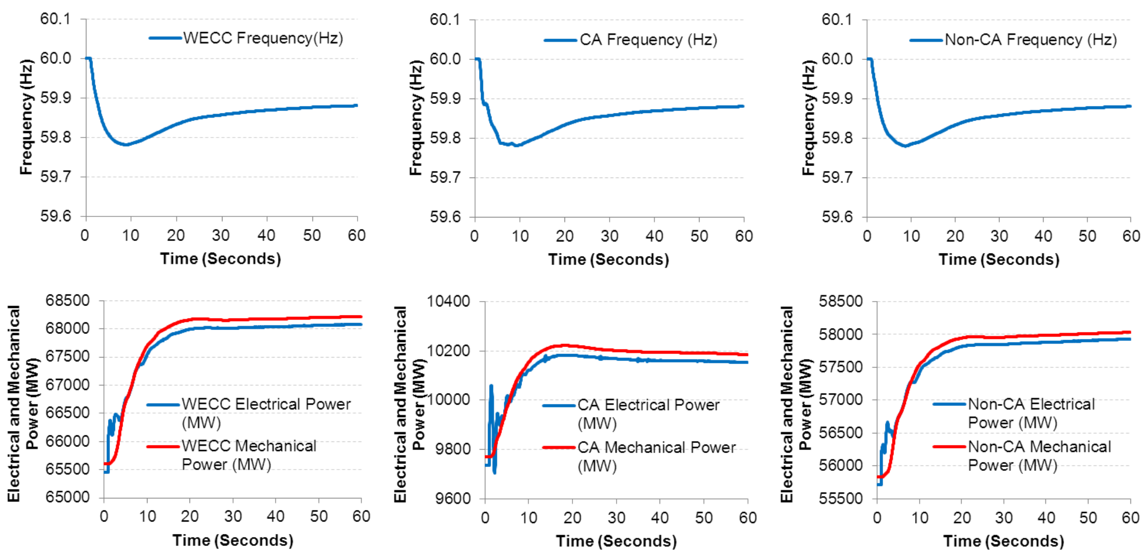

Figure 3-8 Frequency and Governor Response to Loss of Two Palo Verde Units

Table 3-4 Performance Metrics for Spring Peak – High Hydro and Wind Base Case

	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.78	59.78	59.78
Frequency Nadir Time (Seconds)	8.76	9.22	8.67
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	1225	1227	1221
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	907	182	710
Percent of Total (%)		20.1	78.3
Settling Frequency (Hz)	59.88	59.88	59.88
NERC Frequency Response (MW/0.1Hz)	2247	2247	2248
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	1663	334	1307
Percent of Total (%)		20.1	78.6

3.5. GOVERNOR RESPONSE DISCUSSION

The impact of speed and withdrawal of governor response on frequency response is discussed in this section.

3.5.1. SPEED OF GOVERNOR RESPONSE

The speed of response of active governors has a substantial impact on the severity of frequency excursions, especially the depth of the frequency nadir. In this section, we examine the performance of individual units in the system, with a view towards understanding the diverse responses, and how they produce the observed aggregate result.

Figure 3-9 shows the timing of governor response to the loss of two Palo Verde Units event for the Winter Low Load – High CAISO Wind Base Case. Each point in the scatter plot represents one responsive machine, and is located at the time (x-axis) and amplitude (y-axis) of the maximum mechanical power output of the unit. To help understand the figure, four time traces are shown on the right-hand side, for the four red points in the scatter plot. The first of these four plants, at bus # 22983 (thermal generator at Imperial Valley), rises rapidly, and produces its maximum output shortly before frequency nadir. This governor shows some overshoot (about

20%), as compared to the next unit, bus # 22262 (Palomar combined-cycle gas unit located in San Diego), which reaches its maximum output almost as quickly, but has no overshoot. The third unit, at bus # 29209 (steam unit at Blythe power plant in Southern California), responds rapidly, but then swings back – contributing very little by 60 seconds, when the NERC frequency response is measured (in this study). The final unit, at bus # 40365 (Dworshak hydro power plant in northwest Idaho), which happens to be a hydro machine, exhibits the characteristic transient decline on output about 1 or 2 seconds into the event, and then steadily increases output. It is still increasing output at the end of one minute. Not surprisingly, this type of unit is quite important to the frequency response metric. Its contribution to minimizing the frequency nadir *appears to be* lower, but as a percent of initial output, the increase by the time of the nadir (~10 seconds) is higher. In WECC, the contribution of hydro is, not surprisingly, quite important to frequency response.

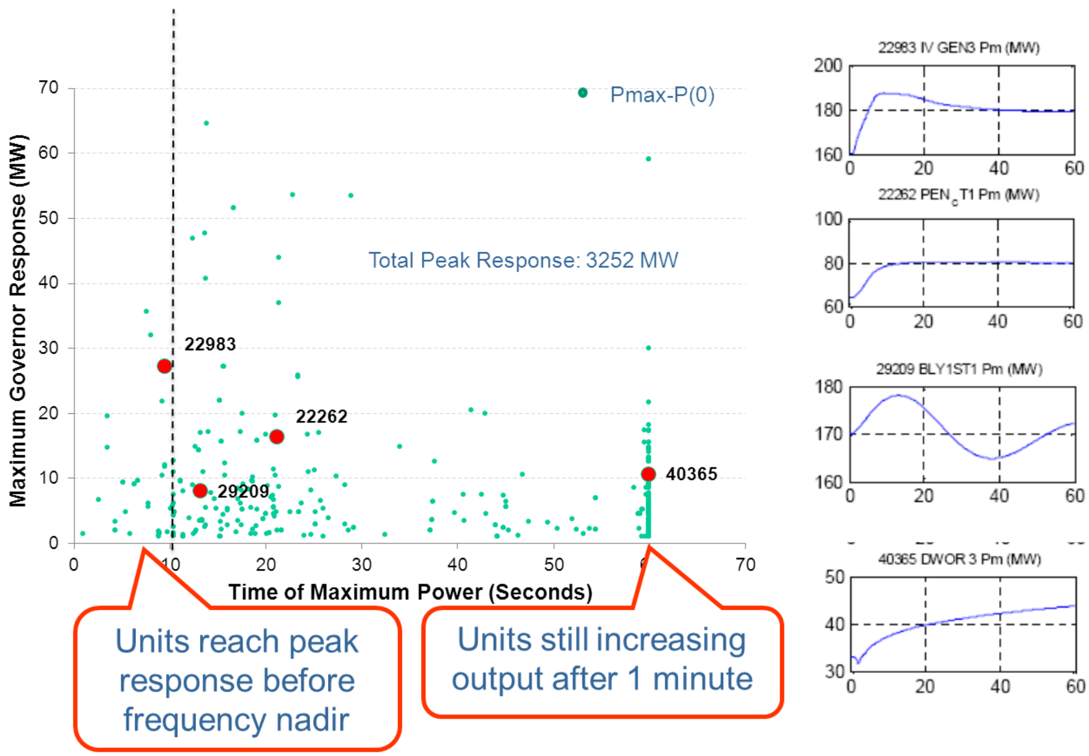

Figure 3-9 Timing of Governor Response for the Winter Low Load – High CAISO Wind Base Case

For a closer inspection, ***Figure 3-10*** shows the governor response of three selected units. The responses are shown in time and as power vs. frequency plane. The traces on the P vs. f plane plot highlight the relationship between power output and the system frequency. For example, Unit A produces its maximum power (an increase of about 3%) just about at the nadir, but withdraws nearly all of its response. Thus, this unit helps the frequency nadir, but contributes almost nothing to the nominal (NERC) frequency response metric. In comparison, Unit B increases its output about 3% by the time of the nadir, but continues to increase, providing about 6-7% increase by 60 seconds. This unit helps both the frequency nadir and frequency response. The response of Unit C is rather more extreme, and not representative of many machines in the model. The output increases very rapidly, helping arrest the rate of frequency decline before the nadir. The output increases by about 10%, but then begins to decline rapidly, even before the time of the frequency nadir, returning to essentially no response. While this response is clearly beneficial, it is also clear qualitatively that to have a large fraction of generation exhibiting this behavior would likely be problematic.

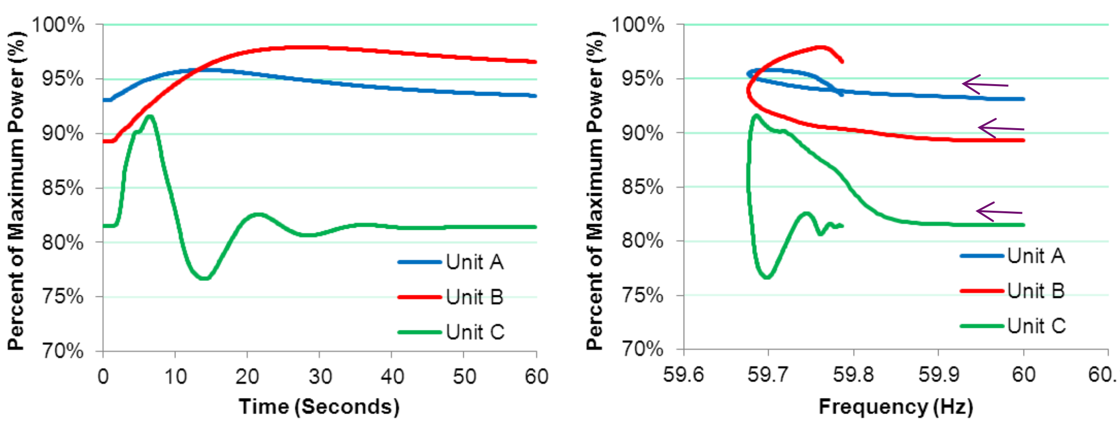

Figure 3-10 Comparison of Governor Response for the Winter Low Load – High CAISO Wind Base Case

Looking at the response of all of the large machines with active governors reinforces the diversity of responses. ***Figure 3-11*** shows the governor response of units with initial generation greater than 300 MW to loss of two Palo Verde Units event in the Winter Low Load – High CAISO Wind Base Case.

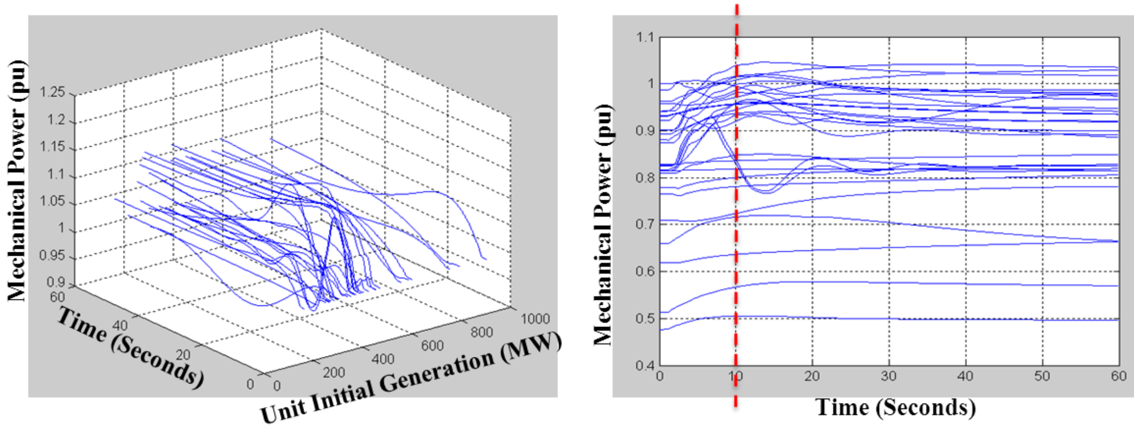

Figure 3-11 Governor Response of Units with Initial Generation Greater 300 MW for the Winter Low Load – High CAISO Wind Base Case

Figure 3-12 shows the timing of governor response to loss of two Palo Verde Units event for the Weekend Morning – High CAISO Wind and Solar Base Case. The distribution of the response characteristics for this case is similar to the Winter case.

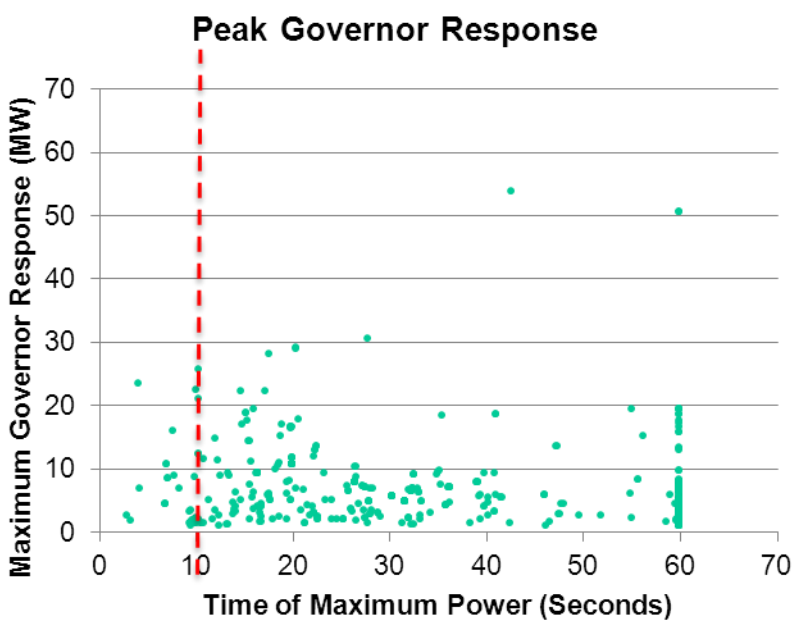

Figure 3-12 Timing of Governor Response for the Weekend Morning – High WECC Wind and Solar Base Case

The main conclusion from this exercise is that there is significant diversity in dynamic response of generation with active governors, that doesn't lend itself well to simple metrics. NERC frequency response may well be an adequate metric of system performance, but it is clear that the reality of the contribution of the different generators to overall performance is rather more complex.

3.5.2. GOVERNOR WITHDRAWAL

The fact that many machines in the WECC system have various load controls that tend to withdraw frequency response is a concern. In the time frame of these simulations, the exact character of the governor withdrawal is, as we observed above with governor response, widely varied. ***Figure 3-13*** shows the governor withdrawal for the loss of two Palo Verde units for the Winter Low Load – High CAISO Wind Base Case. It was assumed that any machine that is producing less power at 60 seconds than it did at any point earlier in the simulation was exhibiting withdrawal. This simplification does not take into account whether the reduction from peak output was due to deliberate control action to reset output, due to control overshoot, or due to the recovery of the frequency. All three of these could be the case, and they are not mutually exclusive. The plot shows the withdrawal, defined here as the difference between the peak post-disturbance output, and the output at the end of the simulation. The withdrawal is plotted against the initial power output of the plant. Again we show four units for context on the right, with matching red points in the scatter plot. In this case, the first three units appear to be deliberately withdrawing output, whereas the fourth unit, bus # 64046, gives sustained output, after what appears to be simple control overshoot.

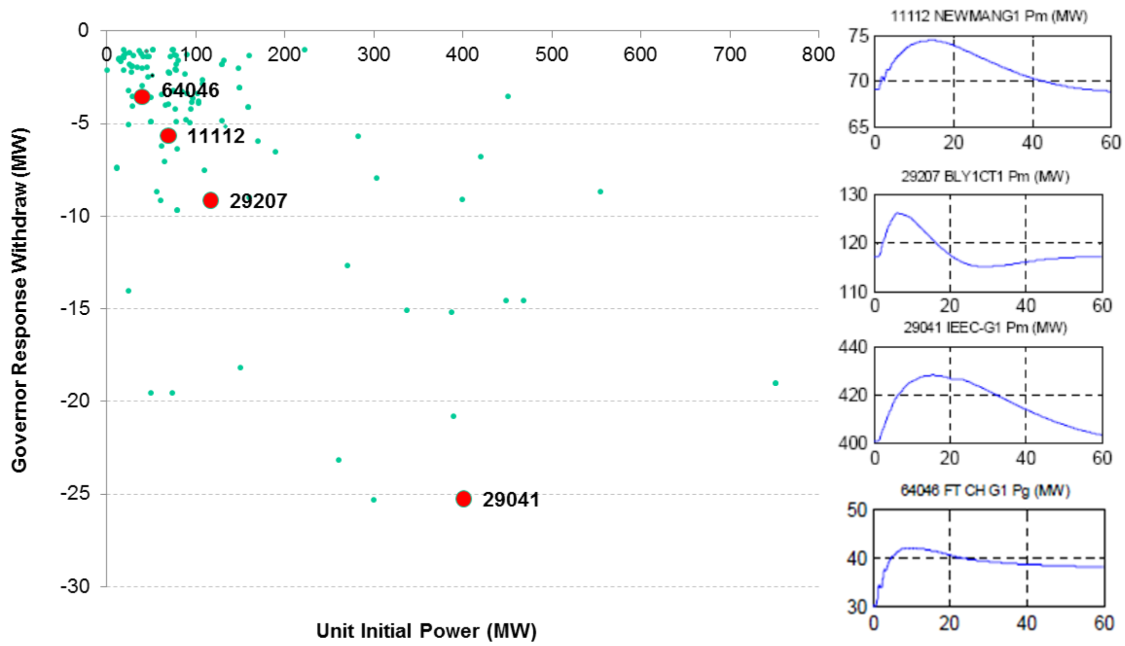

Figure 3-13 Governor Withdrawal for the Winter Low Load – High CAISO Wind Base Case

To further investigate, the dynamic governor models were inventoried for control functions that deliberately reset power output, defeating the governor response. In this case, 18 governor response (GR) units with total power generation of 5338 MW and total generation capacity of 6273 MW have the turbine load controller model (lcfb1). The lcfb1 model represents a supervisory turbine load controller that acts to maintain turbine power at a set value by continuous adjustment of the turbine governor speed-load reference. The lcfb1 is intended to represent slow reset outer loop controllers managing the action of the turbine governor.

Figure 3-14 shows the response of the load controls to the loss of two Palo Verde units. The left figure shows the individual governor response for the 18 units with lcfb1 model, and right figure shows the sum of all governor response for the 18 units with the lcfb1 model. From this plot, we surmise that about 200 MW of governor response – *all of the response of the units* - is deliberately withdrawn by 60 seconds, representing almost 10 percent of total frequency response. This impact is explored further below in Section **Error! Reference source not found.**

Error! Reference source not found. shows a scatter plot similar to ***Figure 3-13***, but for the Weekend Morning – High WECC Wind and Solar Base Case. The behaviors are similar.

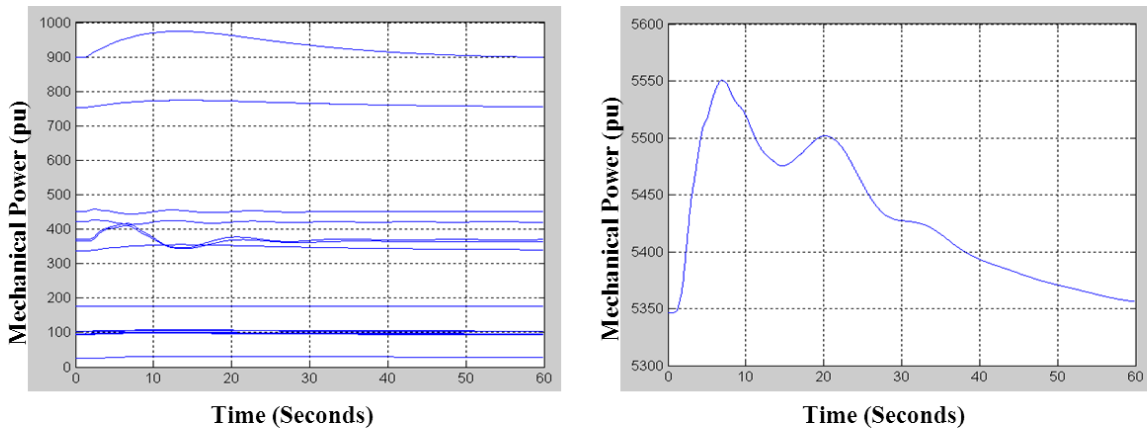

Figure 3-14 Load Control Response for the Winter Low Load – High CAISO Wind Base Case

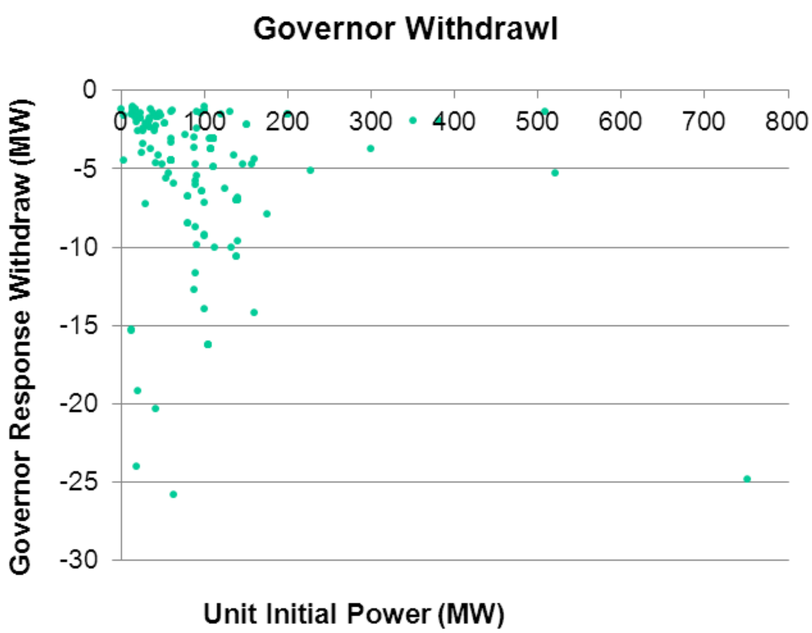

Figure 3-15 Governor Withdrawal for the Weekend Morning – High WECC Wind and Solar Base Case

3.6. SINGLE PALO VERDE TRIP EVENT

This section provides a closer inspection of a less severe event, with the intent of examining some details of the system performance, including load response and sensitivity of FRO to event size. Here a single Palo Verde unit, dispatched at 1345 MW, is tripped.

The frequency, shown in ***Figure 3-16*** reaches a nadir of 59.85Hz. This is consistent with actual CAISO experience with this event. CAISO generation and load response are shown in ***Figure 3-17*** and illustrate some behavior that was not shown in earlier cases. The total governor response, shown in the upper left-hand block is about 250 MW, which is proportionally similar to the larger events shown. CAISOs portion of this is about 200 MW. However, the total and the change in power exchange between California and the rest of WECC is given in the upper right-hand trace. By this measure, California only picks up about 150 MW of the 1344 MW event. The change in flow across COI, shown in the lower right-hand trace, is about 600 MW. This is consistent with the expected re-distribution of flows following the Palo Verde event (and consistent with observed behavior). But the load response, shown in the lower left, *increases* by about 100 MW. This result seems at odds with the expectation that load would drop somewhat with frequency. We examine this behavior more closely in the next subsection.

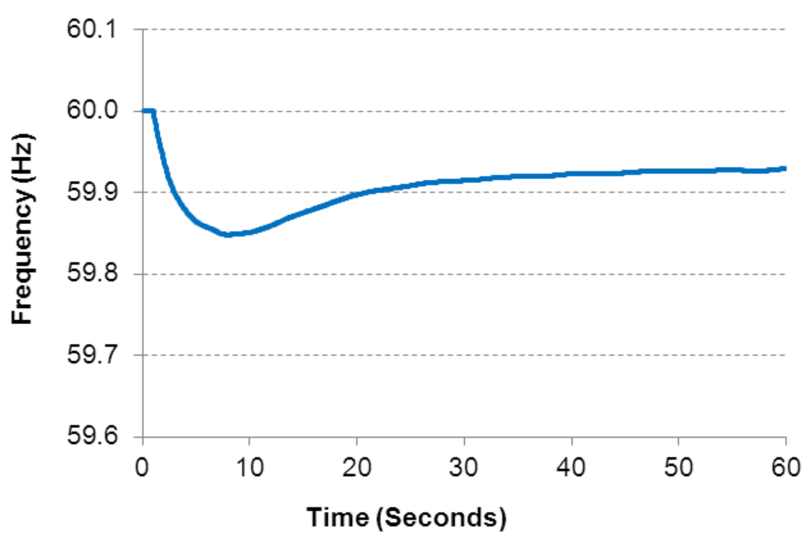

Figure 3-16 Frequency Response to the Trip of One Palo Verde Unit

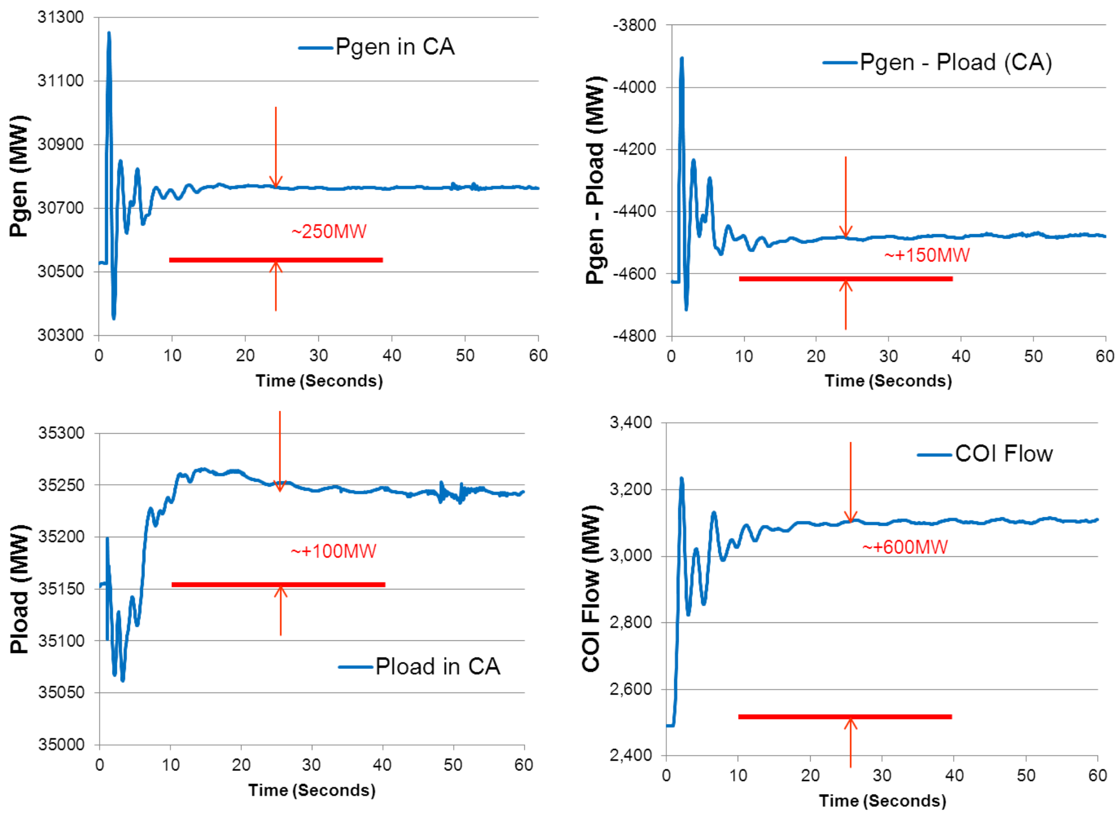

Figure 3-17 Response of California Generation, Load and COI Flow to the Trip of One Palo Verde Unit

3.6.1. DISCUSSION OF LOAD VOLTAGE AND FREQUENCY RESPONSE

Figure 3-18 shows the load voltage and frequency response for the loss of one Palo Verde unit event. In the left column, the first plot shows California frequency. The blue curve in the second plot shows California static load that is voltage dependent (i.e. it shows the impact of the ZIP (Impedance, Current, Power) coefficients that dictate the algebraic change in power with voltage on the static load) and red curve shows California static load that is voltage and frequency dependent (i.e. the ZIP related effect *plus* the frequency sensitive term. The third plot shows the California Dynamic load. The fourth plot show the California total load. The four plots in the second column show the similar information for Non-California.

The results are somewhat surprising. In California, the rise in voltage due to flow redistribution causes a much greater increase due to load voltage sensitivity (the blue trace) than the decrease due to the small frequency drop. In the rest of WECC, the voltage changes less, and so the frequency term really causes the net load to drop. Remember that a 150 mHz excursion is only ¼ of a percent – voltages can easily change several percent, making the change in the "ZIP" contribution relatively large. That appears to be the case here, and raises cautionary point about measurement of frequency response of generation: simply looking at changes in interface flow maybe misleading.

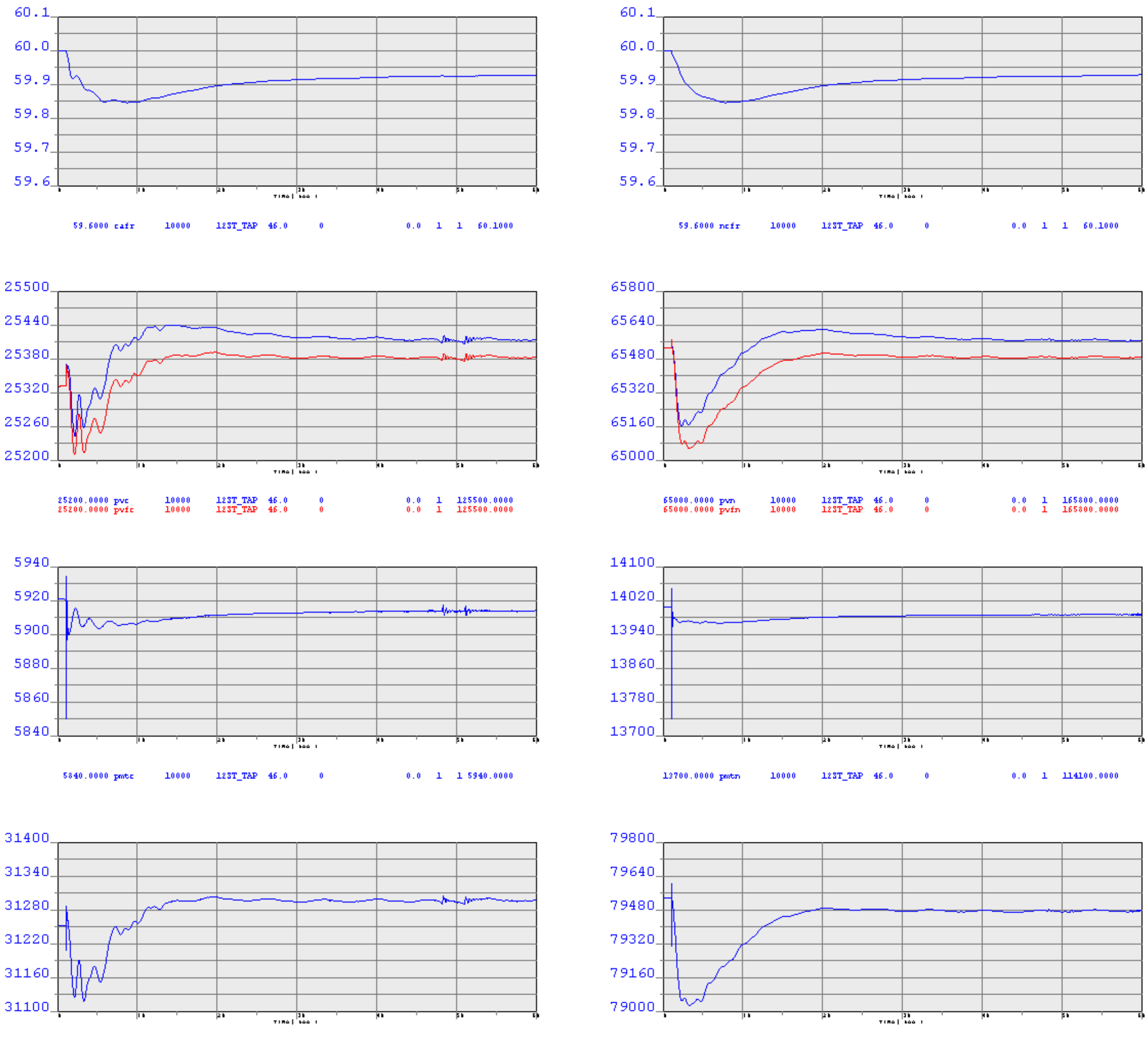

Figure 3-18 Details of Load Voltage and Frequency Sensitivity

4. FREQUENCY PERFORMANCE OF HIGHER RENEWABLE PENETRATION CASES

The frequency response of cases with higher levels of renewable generation outside of California is discussed in this section.

4.1. WINTER LOW LOAD – HIGH WECC WIND CASE

The level of wind generation outside of California in the base case provided by CAISO was relatively low, especially compared to the levels within California. In order to test conditions under which the rest of non-California WECC are also host to significant amounts of wind generation, a new case was developed. The addition of the wind displaces other generation, and as we have shown above, the commitment and dispatch is critical to determining the frequency response.

4.1.1. RE-DISPATCH METHODOLOGY

The Western Wind and Solar Integration Study's (WWSIS) 2/3 de-commitment, 1/3 re-dispatch approach (2/3-1/3 "rule") has been used in this study to add more wind power and re-dispatch the thermal units. The 2/3-1/3 "rule" means that for every 3 MW of additional wind production, there is on average a 2 MW reduction in thermal unit commitment and a 1 MW reduction in thermal unit dispatch. This rule is based on average impact on commitment and dispatch from the extensive Multi-Area Production Simulation (MAPS) production simulations for high wind in WECC made in the WWSIS study [6].

As mentioned before, the selection of conventional thermal units to be replaced by wind turbine generator is based on MAPS results in the WWSIS study. The committed thermal units that have the least annual operating time in MAPS's hourly simulations were selected to be replaced by wind turbine generators. The newly added wind turbine generators were assumed to be operating at 50% rated capacity, in order to capture the operational reality that all wind plants in a system are essentially *never* operating simultaneously at rated power. This assumption for the incremental plants gives a reasonable, if somewhat simple, distribution of loadings on the wind plants in WECC. Thus, in this case, 9508 MW of wind turbines were added to achieve this increased net wind dispatch of 4754 MW.

Fifty conventional thermal units, with total power generation of 4754 MW and total MVA rating of 7888 MVA, were selected to be replaced by WTGs. To satisfy the 2/3-1/3 rule, 418 conventional thermal units (machines with MVA rating greater than 40

MVA), with total power generation of 67166 MW and total MVA rating of 94009 MVA, had their MVA rating and MWCAP modified. This replacement, rerating and re-dispatch results in a net decrease of 3169 MVA of committed units and a net increase of 1585 MW unloaded generation – that is 2 MW de-committed and 1 MW dispatched back for each 3 MW of wind power. Note that the increase in headroom is 1211 MW, since some downwardly dispatched machines do not have governors.

The newly added wind turbine generators and the replaced conventional thermal units in each affected area are summarized in ***Table 4-1***. The second row shows the count by area and MVA of thermal units that were replaced by wind plants. The generation summary for the Winter Low Load – High WECC Wind Case is shown in ***Table 4-2.***

Table 4-1 Type 3 WTGs Added in Non-California Area

Area	11	14	18	40	54	64	65	70	Total
Number of Wind Plant Added	9	8	7	8	2	4	6	5	50
Generation (MW)	645	1008	355	809	281	420	781	455	4754
Displaced Thermal Machine Rating (MVA)	1054	1414	572	1117	347	869	1297	1218	7888

Table 4-2 Generation Summary for Winter Low Load – High WECC Wind Case

	WECC		CA		Non-CA	
		# of Units		# of Units		# of Units
GR Pgen (MW)	33586	496	6602	122	26984	374
GR MWCAP (MW)	48536		10946		37590	
GR Headroom (MW)	14950		4344		10606	
BL Pgen (MW)	30171	298	11223	138	18948	160
NG Pgen (MW)	9678	320	2617	99	7060	221
Wind Pgen (MW)	18094		8411		9684	
Solar Pgen (MW)	2550		2550		0	
MW Capability	109029		35747		73282	
CU Pgen (MW) (GR + BL + NG)	73435	1114	20442	359	52992	755
Total Pgen (MW)	94392		29683		64710	
Total Pload (MW)	91300		26190		65111	
Wind Pgen/Total Pgen	19.2%		28.3%		15.0%	
Solar Pgen/Total Pgen	2.7%		8.6%		0.0%	
Kt	44.5%		30.6%		51.3%	
GR Pgen/CU Pgen	45.7%	44.5%	32.3%	34.0%	50.9%	49.5%
GR Pgen/Total Pgen	35.6%		22.2%		41.7%	
GR Headroom/CU Pgen	20.4%		21.3%		20.0%	
GR Headroom/Total Pgen	15.8%		14.6%		16.4%	

Table 4-3 Wind and Solar Power Summary for Winter Low Load – High CAISO Wind Case

	WECC	CA	Non-CA
TOTAL Pgen	94392	29683	64710
TOTAL Pload	91300	26190	65111

WIND&SOLAR (MW)

	WECC		CA		Non-CA	
TP 1	2494(wind)	398(solar)	2160(wind)	398(solar)	334(wind)	0(solar)
TP 2	444(wind)		444(wind)		0(wind)	
TP 3	9809(wind)		5213(wind)		4597(wind)	
TP 4	594(wind)	1738(solar)	594(wind)	1738(solar)	0(wind)	0(solar)
epcgen		414(solar)		414(solar)		0(solar)
Total	13341(wind)	2550(solar)	8411(wind)	2550(solar)	4930(wind)	0(solar)
W&S/Pgen	14.1%(wind)	2.7%(solar)	28.3%(wind)	8.6%(solar)	7.6%(wind)	0.0%(solar)

Table 4-4 Wind and Solar Power Summary for Winter Low Load – High WECC Wind Case

	WECC	CA	Non-CA
TOTAL Pgen	94392	29683	64710
TOTAL Pload	91300	26190	65111

WIND&SOLAR (MW)

	WECC		CA		Non-CA	
TP 1	2494(wind)	398(solar)	2160(wind)	398(solar)	334(wind)	0(solar)
TP 2	444(wind)		444(wind)		0(wind)	
TP 3	14563(wind)		5213(wind)		9350(wind)	
TP 4	594(wind)	1738(solar)	594(wind)	1738(solar)	0(wind)	0(solar)
epcgen		414(solar)		414(solar)		0(solar)
Total	18094(wind)	2550(solar)	8411(wind)	2550(solar)	9684(wind)	0(solar)
W&S/Pgen	19.2%(wind)	2.7%(solar)	28.3%(wind)	8.6%(solar)	15.0%(wind)	0.0%(solar)

4.1.2. LOSS OF PALO VERDE EVENT

Figure 4-1 shows that this new case with more wind has better frequency response. The dispatch increased headroom when wind generation was added - nowhere near in proportion to the amount of wind generation added, but about 1300MW, which helped the system response. The Kt for this case is essentially the same. So again, it appears that headroom and Kt are better metrics of anticipated performance, and renewable penetration alone gives little insight. Loss of inertia, as measured by initial rate-of-change-of-frequency (ROCOF), with the change case is nearly invisible.

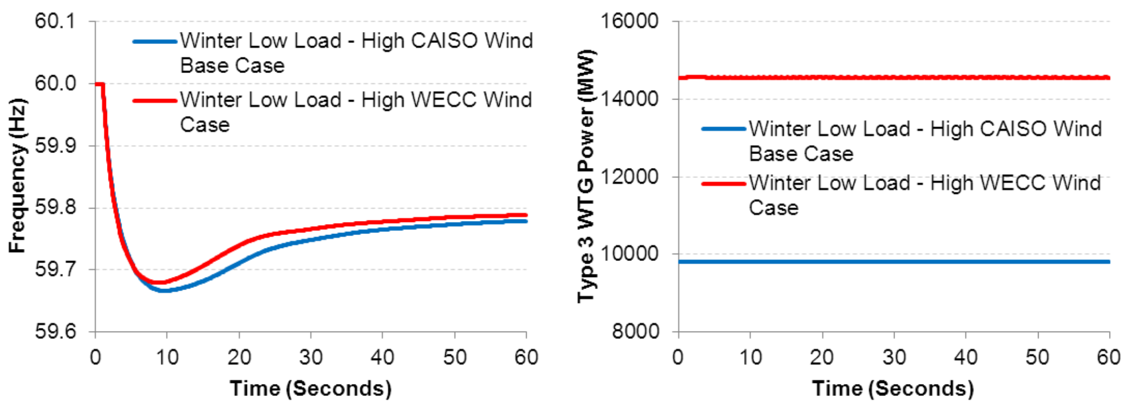

Figure 4-1 Impact of Increasing Levels of Wind on Frequency Performance

Table 4-5 Comparison of Performance Matrix of Increasing Levels of Wind on Frequency Performance to Loss of Two Palo Verde Units

	Winter Low Load – High CAISO Wind Base Case			Winter Low Load – High WECC Wind Case		
	WECC	CA	Non-CA	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.67	59.66	59.67	59.68	59.68	59.68
Frequency Nadir Time (Seconds)	9.8	8.7	9.9	9.1	8.5	9.3
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	806	801	810	839	834	836
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	641	154	479	675	176	500
Percent of Total (%)		24.0	74.7		26.1	74.1
Settling Frequency (Hz)	59.78	59.78	59.78	59.79	59.79	59.79
NERC Frequency Response (MW/0.1Hz)	1218	1217	1226	1272	1272	1271
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	968	234	726	1024	269	760
Percent of Total (%)		24.2	75.0		26.3	74.2

4.2. WEEKEND MORNING – HIGH WECC WIND AND SOLAR

The intention of Weekend Morning – High WECC Wind and Solar Case was to capture high stressed "Saturday morning" condition, i.e. high wind and solar with moderate load. For the Weekend Morning – High CAISO Wind and Solar Base Case, the units' commitment and dispatch in California is reasonable and the instantaneous penetration of wind and solar power is around 50%. However, the rest of WECC is not very stressed, i.e., relatively low wind, and lots of responsive generation with adequate headroom is committed. A large fraction of the responsive generation in WECC is hydro under these load and water conditions.

In order to create a highly stressed system, many of the thermal and hydro units that provide frequency response were de-committed and replaced by wind turbine generators outside of California. Specifically, frequency responsive hydro units in BPA's area were selected to be replaced by wind turbine generators. Displacement of responsive hydro machines in the Pacific Northwest has been raised as a concern regarding WECC frequency response.

New wind generation totaling 9042 MW is added with 18084 MW nameplate (50% of rating), for a total of 30512 MW of installed wind rating in WECC. The net result is that the system has substantially lower spinning reserves, lower Kt, and higher instantaneous wind penetration. Note that in this case, the higher level of wind generation in WECC is largely arbitrary. The generation summary for the Weekend

Morning – High WECC Wind and Solar Case is shown in ***Table 4-6***. The overall instantaneous penetration of wind and solar is 50% in California, and 25% for WECC in total.

Table 4-6 Generation Summary for Weekend Morning – High WECC Wind and Solar Base Case

	WECC		CA		Non-CA	
		# of Units		# of Units		# of Units
GR Pgen (MW)	38590	678	5514	127	33075	551
GR MWCAP (MW)	51587		9785		41802	
GR Headroom (MW)	12997		4271		8727	
BL Pgen (MW)	37384	431	9478	155	27906	276
NG Pgen (MW)	9603	453	1757	121	7845	332
Wind Pgen (MW)	21762		8646		12428	
Solar Pgen (MW)	6810		6667		144	
MW Capability	127146		36333		90125	
CU Pgen (MW) (GR + BL + NG)	85577	1562	16749	403	68826	1159
Total Pgen (MW)	114775		30525		84250	
Total Load (MW)	110798		35155		75643	
Wind Pgen/Total Pgen	19.0%		28.3%		14.8%	
Solar Pgen/Total Pgen	5.9%		21.8%		0.2%	
Kt	40.6%		26.9%		46.4%	
GR Pgen/CU Pgen	45.1%	43.4%	32.9%	31.5%	48.1%	47.5%
GR Pgen/Total Pgen	33.6%		18.1%		39.3%	
GR Headroom/CU Pgen	15.2%		25.5%		12.7%	
GR Headroom/Total Pgen	11.3%		14.0%		10.4%	

Table 4-7 Wind and Solar Power Summary for Weekend Morning – High CAISO Wind and Solar Base Case

```
                 WECC              CA         Non-CA
 TOTAL Pgen         114775        30525         84250
 TOTAL Pload        110787        35152         75635

WIND&SOLAR (MW)
                 WECC                        CA                          Non-CA
 TP 1      3219(wind)  398(solar)       2281(wind)  398(solar)       938(wind)    0(solar)
 TP 2       990(wind)                    301(wind)                     0(wind)
 TP 3      7917(wind)                   5469(wind)                  2448(wind)
 TP 4       594(wind) 4360(solar)        594(wind) 4319(solar)         0(wind)   40(solar)
 epcgen               2052(solar)                  1949(solar)                  103(solar)

 Total    12720(wind) 6810(solar)       8645(wind) 6666(solar)      3386(wind)  144(solar)

W&S/Pgen 11.1%(wind)  5.9%(solar)     28.3%(wind)21.8%(solar)       4.0%(wind) 0.2%(solar)
```

Table 4-8 Wind and Solar Power Summary for Weekend Morning – High WECC Wind and Solar Base Case

	WECC	CA	Non-CA
TOTAL Pgen	114775	30525	84250
TOTAL Pload	110787	35152	75635

WIND&SOLAR (MW)

	WECC		CA		Non-CA	
TP 1	3219(wind)	398(solar)	2281(wind)	398(solar)	938(wind)	0(solar)
TP 2	990(wind)		301(wind)		0(wind)	
TP 3	16959(wind)		5469(wind)		11489(wind)	
TP 4	594(wind)	4360(solar)	594(wind)	4319(solar)	0(wind)	40(solar)
epcgen		2052(solar)		1949(solar)		103(solar)
Total	21762(wind)	6810(solar)	8645(wind)	6666(solar)	12428(wind)	144(solar)
W&S/Pgen	19.0%(wind)	5.9%(solar)	28.3%(wind)	21.8%(solar)	14.8%(wind)	0.2%(solar)

4.2.1. RESPONSE TO PALO VERDE DISTURBANCE

The performance of this case, as shown in ***Figure 4-2***is still satisfactory, in that UFLS is avoided, with a total margin of about 110 mHz. But, as expected the performance is worse compared to the same case with less wind generation outside of California. The LBNL nadir base metric drops to just below 700 MW/0.1 Hz. Interestingly, with increased wind penetration outside of California, California's frequency response improves (from 286 to 311 MW/0.1 Hz – well above the 205 MW/0.1Hz target) and the fractional contribution increases greatly, from 20% to 27%. The behavior of resources outside of California has impact on the California response. The poorer performance of this case notwithstanding, the frequency response behavior for this case, in which headroom and Kt were deliberately aggressively reduced, is acceptable from the primary perspective of avoiding UFLS and other stability problems.

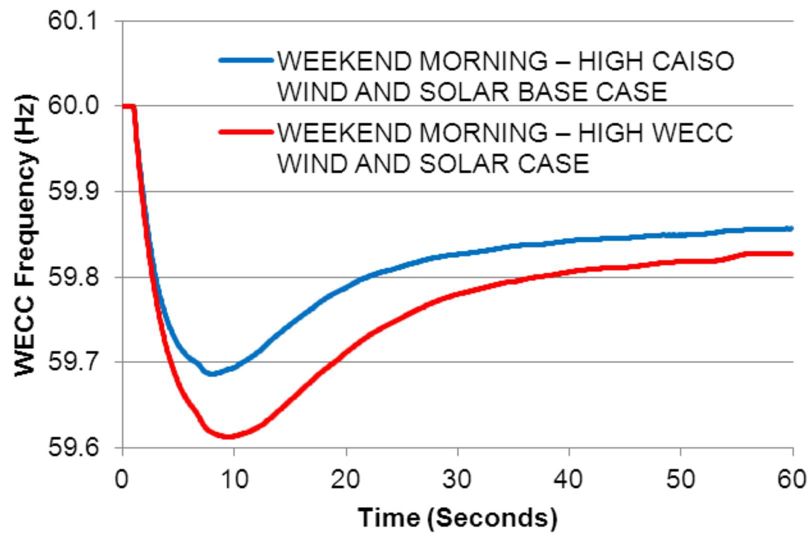

Figure 4-2 Frequency Response to Loss of Two Palo Verde Units

Table 4-9 Comparison of Performance Matrix of Increasing Levels of Wind to Loss of Two Palo Verde Units

	Weekend Morning – High CAISO Wind and Solar Base Case			Weekend Morning – High WECC Wind and Solar Case		
	WECC	CA	Non-CA	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.69	59.68	59.68	59.61	59.61	59.61
Frequency Nadir Time (Seconds)	8.0	8.8	7.8	9.7	9.9	9.1
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	858	852	853	695	684	697
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	658	134	503	515	140	354
Percent of Total (%)		20.0	76.0		27.0	69.0
Settling Frequency (Hz)	59.86	59.85	59.86	59.83	59.82	59.83
NERC Frequency Response (MW/0.1Hz)	1878	1824	1893	1565	1520	1578
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	1440	287	1116	1158	311	802
Percent of Total (%)		20.0	78.0		27.0	69.0

5. FACTORS AFFECTING FREQUENCY RESPONSE UNDER HIGH PENETRATION OF RENEWABLES

In this section, we explore a range of factors that are expected to impact frequency performance. The table below provides a high level, qualitative view of the expected impact of various changes on both the frequency nadir and on the settling frequency. The following sections examine these sensitivities, and test the hypotheses of these table entries

Table 5-1 Factors Affecting Frequency and Expected Impact on Frequency Performance

	Impact on Frequency Nadir	Impact on Settling Frequency
Reduced Inertia	Worse, sooner	No impact
Reduced Headroom	Small impact	Worse
Reduced Count of Governors Enabled	Small impact	Worse
More Governor Withdrawal	Small impact	Worse
Wind Inertial Control	Improve	Small impact
Wind Frequency Droop (Governor-Like Control)	Improve	Improve

5.1. FACTORS DEGRADING FREQUENCY RESPONSE

5.1.1. REDUCED INERTIA

During industry discussions of the impact of wind and solar generation on frequency response, there has been widespread confusion (or at the least, imprecision) about the impact of inertia. It is well understood that variable speed wind generation, PV and other generation technologies that rely on power inverters, do not contribute to system inertia, unless controls are provided to do so. However, discussion about the perceived impact of this specific aspect of wind and solar generation has often expanded to include the broader issues associated with primary, and even secondary frequency response. The test case presented here was constructed to vary only system inertia, and to keep all the other factors impacting frequency response as close as possible to the comparison case.

For the initial conditions of this case, we started with the Winter Low Load – High CAISO Wind Base Case. In order to hold other frequency response aspects the same, we left the commitment and dispatch of all units with active governors the same: in effect freezing Kt and headroom. Wind and solar were similarly held constant. Baseload units, which only contribute inertia to the system frequency response were decommited, and other baseload units dispatched upward. Specifically, we de-committed 14 baseload units, with a total MVA rating = 1992.7 MVA and Pgen = 323.7 MW. Two other baseload units, with total MVA rating = 1762.4 MVA and Pgen = 591 MW were selected to dispatch up 323.7 MW.

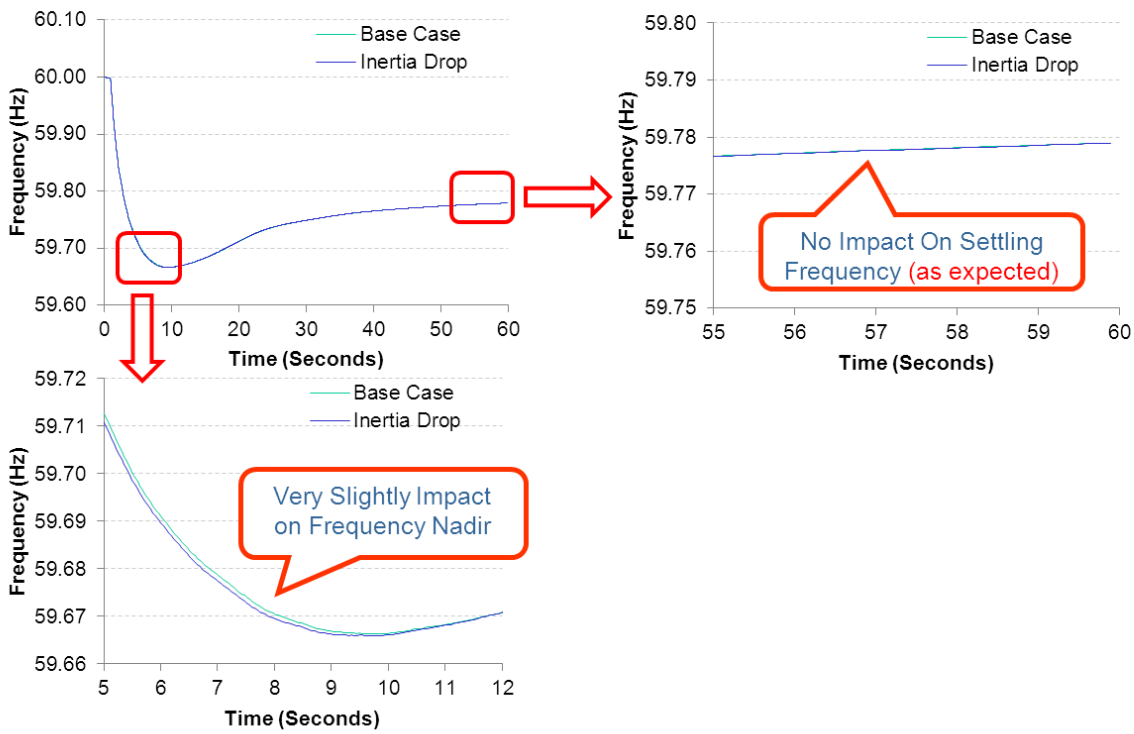

Figure 5-1 Impact of Reduced Inertia on Frequency Performance to Loss of Two Palo Verde Units

Details of the frequency response are shown in ***Figure 5-1***. In the figure, we zoom in on the frequency nadir and on the settling frequency. The impact of loss of inertia for 2000MVA is nearly invisible. This is consistent with the findings of the LBNL report [3,5].

5.1.2. FEWER GOVERNORS IN OPERATION

In this test case, we attempted to isolate the specific impact of the number or count of units providing governor response. Again, the test case was constructed to vary only the count of units with active governors, and to keep all the other factors impacting frequency response as close to fixed from the comparison case as possible.

To accomplish this, we wanted to keep the headroom the same. Starting from the Winter Low Load – High CAISO Wind Base, 25 governor response units (non-baseload), with a total dispatch (Pgen) of 3144 MW, and rating (MWCAP) of 5189 MW, for a total of (2045 MW headroom) were selected to dispatch up 2045 MW and then were set as baseload. Another 11 governor response units, with total dispatch Pgen = 3034 MW and rating MWCAP= 4165 MW were selected to dispatch down 2045 MW. This reduces the count of generators providing response by 25, while holding headroom fixed.

A summary of results for this modified case is shown in ***Table 5-2***. This compares to the base case shown in ***Table 2-3***. The WECC-wide Kt drops about 5% to 41.6% from 46.5%. California and non-California WECC have similar percentage drops.

Table 5-2 Generation Summary for Winter Low Load – High CAISO Wind Case with Fewer Governors Enabled

	WECC		CA		Non-CA	
		# of Units		# of Units		# of Units
GR Pgen (MW)	30093	488	5574	110	24519	378
GR MWCAP (MW)	43804		8869		34935	
GR Headroom (MW)	13711		3295		10416	
BL Pgen (MW)	37370	344	13039	150	24330	194
NG Pgen (MW)	10849	332	2617	99	8232	233
Wind Pgen (MW)	13341		8411		4930	
Solar Pgen (MW)	2550		2550		0	
MW Capability	107914		35486		72427	
CU Pgen (MW) (GR + BL + NG)	78312	1164	21230	359	57081	805
Total Pgen (MW)	94517		30472		64045	
Total Load (MW)	91301		26190		65111	
Wind Pgen/Total Pgen	14.11%		27.6%		7.7%	
Solar Pgen/Total Pgen	2.7%		8.4%		0.0%	
Kt	40.6%		25.0%		48.2%	
GR Pgen/CU Pgen	38.4%	41.9%	26.3%	30.6%	43.0%	47.0%
GR Pgen/Total Pgen	31.8%		18.3%		38.3%	
GR Headroom/CU Pgen	17.5%		15.5%		18.2%	
GR Headroom/Total Pgen	14.5%		10.8%		16.3%	

The results show that a substantial drop in the count of governors enabled has a big impact on performance. The frequency nadir of 59.61 has only 110 mHz of margin, indicating that the count of governors providing response is quite important. However, some care is needed in reaching conclusions from this case. As the governor response was redistributed, the speed of the governors switched to baseload was not explicitly considered. The scatter plot shown in ***Figure 5-2*** is similar to ***Figure 3-9*** , which was explained earlier. The scatter is for the governor responses in this case. However, in this figure the response of the changed governor response units are highlighted. The blue dots are the response of units in *the base* case that were redispatched to have more headroom in this case, making up for the units with red dots. The red dots are from the base case response – these units don't contribute to response in this case (except, of course for their inertia). In the figure, you can observe that six of the units that would have reached their maximum power output by the time of the frequency nadir around 10 seconds were removed. The conclusion is that both count and speed of governor response is important.

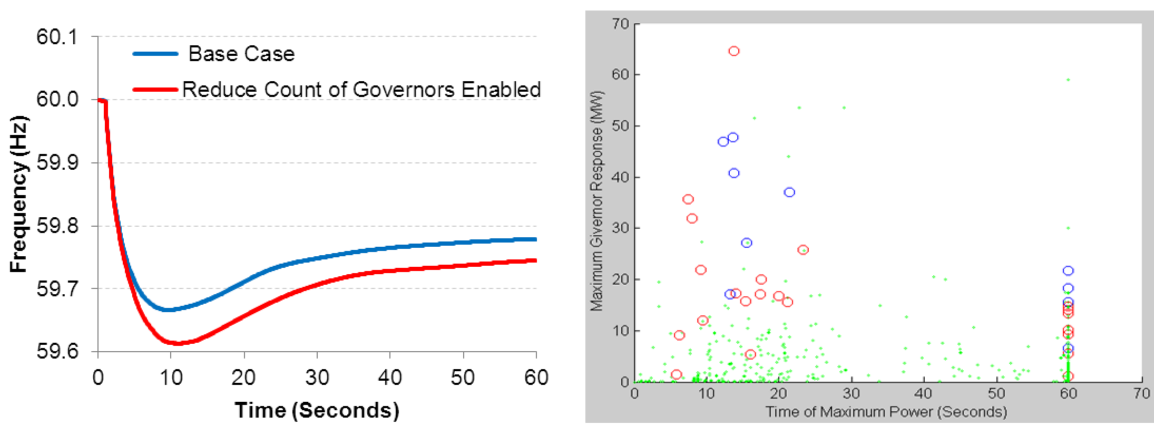

Figure 5-2 Impact of Fewer Governor Enabled on Frequency Performance to Loss of Two Palo Verde Units

5.1.3. REDUCED HEADROOM

In the cases presented so far, we have kept close track of governor headroom. The ability of committed generation to respond quickly and autonomously to changes in system frequency is paramount to issues of frequency response.

We have not generally addressed *how* that headroom is obtained or accounted for in system operations. There are various ancillary services and related metrics that are regularly purchased, or at least tracked. These include various reserve products that include:

- Contingency reserve
- Spinning reserve
- Regulation

We have not tried to establish whether existing ancillary services will result in providing headroom.

In this section, we examine several different cases, with increasingly severe depletion of headroom before the disturbance.

5.1.3.1. SMALL CHANGE IN HEADROOM

In this first test case, we attempted to isolate the specific impact of a small change in headroom only. Again, the test case was constructed to vary only this metric, and to keep all the other factors impacting frequency response, including the count of units with active governors, as close to fixed from the comparison case as possible to test the effect. Several units with active governors were dispatched up, to reduce headroom. Specifically, 19 governor units, with total Pgen = 3105 MW and MWCAP= 5688 MW, were selected to dispatch up 1981 MW. Other baseload generation was dispatched down, with 6 baseload units, with total Pgen = 2081 MW, being selected to dispatch down the same 1981 MW.

The slightly surprising results of this case are shown in ***Figure 5-3***. The performance improves very slightly. The improved performance is likely due to the fact that the governor units have slightly faster governor response at higher initial power levels. But overall, the result is not surprising: when the system has adequate headroom, it does not get exhausted by the grid event. There is therefore *no* impact on settling frequency, and the frequency response metric. In short, headroom only matters if it becomes scarce.

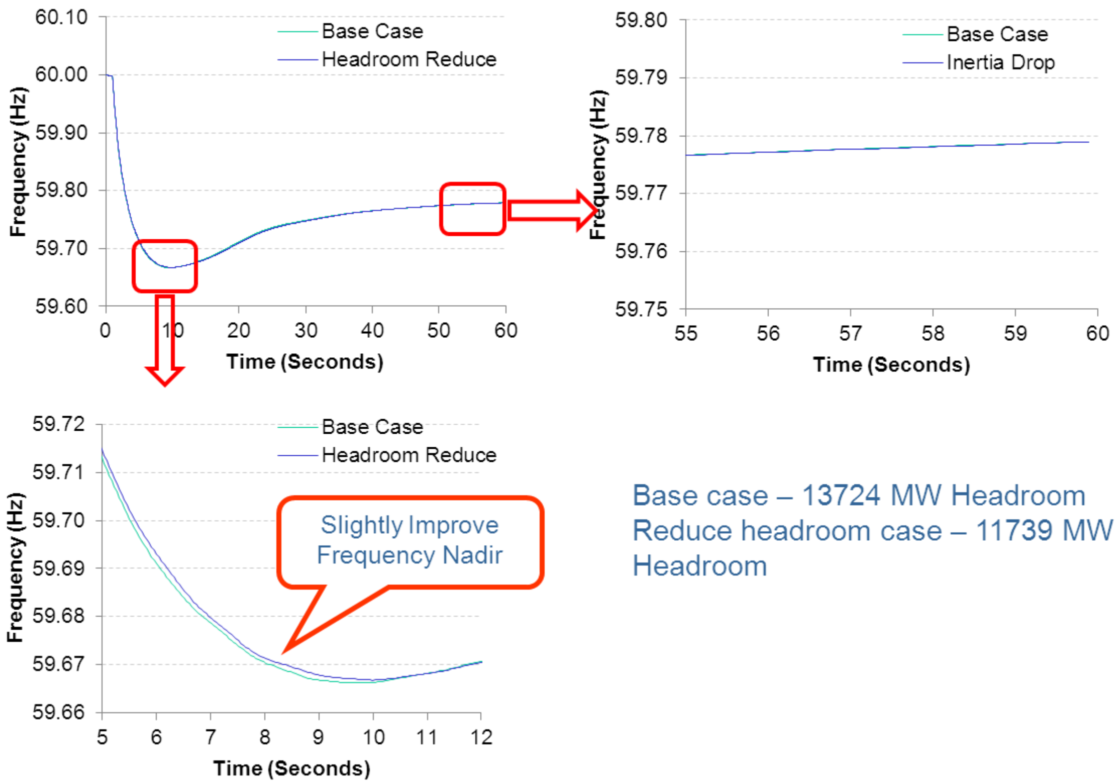

Figure 5-3 Impact of Reduced Headroom on Frequency Performance

5.1.3.2. PRACTICAL MINIMUM HEADROOM

Unlike the previous test case, the system conditions were modified to reflect an operating condition with greatly reduced headroom and Kt. In this case, the overall WECC headroom was reduced to about 8 GW. The system was deliberately stressed to what GE and CAISO consider the practical minimum (whether others agree that this is the practical minimum is open to debate). It is worth noting that the condition from which this case was developed was already considered to be challenging, and representative of a realistic commitment and dispatch for high wind and solar conditions. This case is designed to push headroom down to levels that we believe might occur relatively infrequently.

The case summary table follows: The overall system Kt is reduced to 27% and 26% in California. This is below the 30% level roughly established by the LBNL work as a practical minimum.

Table 5-3 Generation Summary for Winter Low Load – High WECC Wind Case – Practical Minimum Headroom

	WECC		CA		Non-CA	
		# of Units		# of Units		# of Units
GR Pgen (MW)	18942	284	5045	92	13897	192
GR MWCAP (MW)	27057		8169		18888	
GR Headroom (MW)	8115		3124		4991	
BL Pgen (MW)	44815	510	12780	168	32035	342
NG Pgen (MW)	9678	320	2617	99	7060	221
Wind Pgen (MW)	18094		8411		9684	
Solar Pgen (MW)	2550		2550		0	
MW Capability	102194		34527		67667	
CU Pgen (MW) (GR + BL + NG)	73435	1114	20442	359	52992	755
Total Pgen (MW)	94392		29683		64710	
Total Load (MW)	91300		26190		65111	
Wind Pgen/Total Pgen	19.2%		28.3%		15.0%	
Solar Pgen/Total Pgen	2.7%		8.6%		0.0%	
Kt	26.5%		23.7%		27.9%	
GR Pgen/CU Pgen	25.8%	25.5%	24.7%	25.6%	26.2%	25.4%
GR Pgen/Total Pgen	20.1%		17.0%		21.5%	
GR Headroom/CU Pgen	11.1%		15.3%		9.4%	
GR Headroom/Total Pgen	8.6%		10.5%		7.7%	

The performance is shown in ***Figure 5-4***, and performance metrics are reported in ***Table 5-4***. The frequency nadir is 59.55Hz, which gives only 50mHz margin to UFLS. This probably represents the lowest nadir that is likely to be considered acceptable, given a degree of uncertainty about initial (pre-disturbance) frequency.

The graph on the right hand side is adopted from the LBNL report by John Undrill [5]. The two traces are from that report, and show the expected frequency nadir and settling frequency as a function of Kt. The blue and red vertical lines with dot and "X", were added from the results of this study. These annotations correspond to two cases. The vertical line is to emphasize the Kt for the cases, the solid dot is the settling frequency, and the "X" is the frequency nadir.

The first and possibly most important observation is that these results, using the full detailed WECC dynamic dataset, correspond well to the results developed by John Undrill, using a relatively simple generic model. The frequency nadir for our results is somewhat better (higher), which may be due to benefits of load contribution to frequency response, and perhaps effectively faster response by the net of governors. The settling frequency is slightly worse, which could be due to governor withdrawal (see Section **5.2.1**). These results suggest that a minimum Kt of about 0.25 might be acceptable.

When looking at this figure, it is important to remember that Kt, on the right-hand side of the figure, is *only* concerned with the fraction of generation that is contributing governor response. But not how far that generation can *move* – i.e. headroom. It is possible for Kt to remain the same when headroom changes: the two quantities, while related, are separate. Below we will show that too little headroom, even with seemingly adequate Kt, will result in poor performance.

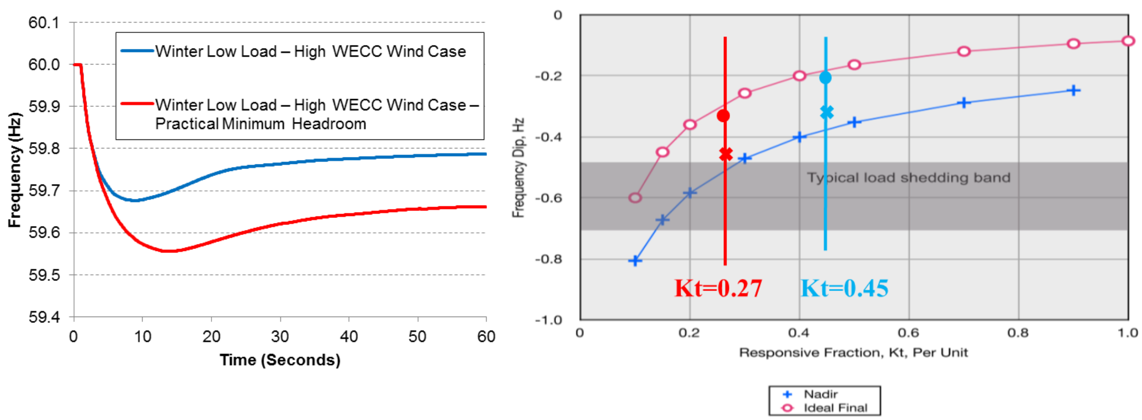

Figure 5-4 Impact of Reduced Headroom and Governor Participation (Kt) on Frequency Performance for Winter Low Load – High WECC Wind Case

Table 5-4 Comparison of Performance Matrix of Reduced Governor Response to Loss of Two Palo Verde Units

	Winter Low Load – High WECC Wind Case			Winter Low Load – High WECC Wind Case – Practical Minimum Headroom		
	WECC	CA	Non-CA	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.68	59.68	59.68	59.56	59.55	59.55
Frequency Nadir Time (Seconds)	9.1	8.5	9.3	13.4	14.6	13.4
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	839	834	836	605	604	598
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	675	176	500	464	171	295
Percent of Total (%)		26.1	74.1		36.9	63.6
Settling Frequency (Hz)	59.79	59.79	59.79	59.66	59.66	59.66
NERC Frequency Response (MW/0.1Hz)	1272	1272	1271	794	795	791
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	1024	269	760	609	224	396
Percent of Total (%)		26.3	74.2		36.8	65.0

5.1.3.3. EXTREME MINIMUM HEADROOM

In this test case, the headroom was reduced to 3 GW. This is essentially equal to the event size. The case is designed as a test, and is not necessarily representative of a condition that is either practical or one that the system operator would regard as acceptable. Rather, we are looking to understand what might happen, and establish a test case on which remediation of extreme conditions might be tested. It is not clear that the system could ever get to this level of stress, although one possible cause might be due to a significantly flawed forecast which resulted in depletion of secondary reserves- a concern that FERC and NERC have raised. To achieve this condition, governor responsive units were dispatched up and baseload generation was backed down, exhausting headroom. It is worth re-emphasizing that this condition corresponds to about 20GW of instantaneous production of wind and solar in WECC. Since one postulated cause of instantaneous operation at such acutely reduced headroom is from an unexpected drop in wind or solar production, one could reasonably suppose that this case is representative of a future condition in which much greater than the 25GW of nameplate/rating of wind + solar of this case is operating in WECC. A final important point for this particular case is that the UFLS was disabled to allow the comparison of frequency response to other cases without the complexity of considering UFLS effects.

The case summary table follows: It is important to note that the redispatch and the definition of Kt here, result in this case having a *higher* Kt than the previous case. This is because Pgen of the baseload units declined, while MWCAP of the governor responsive units stayed the same. Thus, even though this is clearly a more stressed case, the metric Kt (as defined in the study) indicates that it should give more robust performance.

Table 5-5 Generation Summary for Winter Low Load – High WECC Wind Case – Extreme Minimum Headroom Case

	WECC		CA		Non-CA	
		# of Units		# of Units		# of Units
GR Pgen (MW)	23913	284	7018	92	16895	192
GR MWCAP (MW)	27057		8169		18888	
GR Headroom (MW)	3144		1151		1993	
BL Pgen (MW)	39676	510	11439	168	28238	342
NG Pgen (MW)	9678	320	2617	99	7060	221
Wind Pgen (MW)	18094		8411		9684	
Solar Pgen (MW)	2550		2550		0	
MW Capability	97055		33186		63870	
CU Pgen (MW) (GR + BL + NG)	73267	1114	21074	359	52193	755
Total Pgen (MW)	94225		30315		63910	
Total Pload (MW)	91301		26190		65111	
Wind Pgen/Total Pgen	19.2%		27.7%		15.2%	
Solar Pgen/Total Pgen	2.7%		8.4%		0.0%	
Kt	27.9%		24.6%		29.6%	
GR Pgen/CU Pgen	32.6%	25.5%	33.3%	25.6%	32.4%	25.4%
GR Pgen/Total Pgen	25.4%		23.2%		26.4%	
GR Headroom/CU Pgen	4.3%		5.5%		3.8%	
GR Headroom/Total Pgen	3.3%		3.8%		3.1%	

The response of this case is shown in ***Figure 5-5***. The green trace is for this case, and is shown in comparison to the previous, 8 GW headroom case in red and the reference case in blue.

The frequency nadir for this case is 59.42 Hz, which would have impinged on the UFLS threshold – an unacceptable result. The settling frequency is 59.54 Hz – barely above the minimum to avoid UFLS. This is evidence that the performance is limited by the range of available response and the static frequency droop of the governors, and not just the speed of response of the governors.

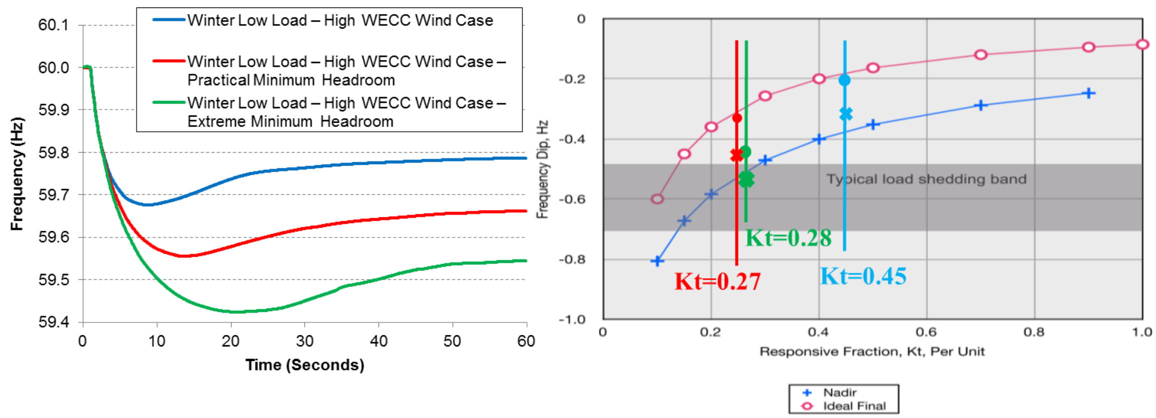

Figure 5-5 Impact of extreme minimum headroom and governor participation (Kt) on Frequency Performance for Winter Low Load – High WECC Wind Case

Table 5-6 Comparison of Performance Matrix of Reduced Headroom Cases

	Winter Low Load – High WECC Wind Case			Winter Low Load – High WECC Wind Case – Practical Minimum Headroom			Winter Low Load – High WECC Wind Case – Extreme Minimum Headroom		
	WECC	CA	Non-CA	WECC	CA	Non-CA	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.68	59.68	59.68	59.56	59.55	59.55	59.42	59.42	59.43
Frequency Nadir Time (Seconds)	9.1	8.5	9.3	13.4	14.6	13.4	20.7	18.8	20.7
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	839	834	836	605	604	598	467	461	468
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	675	176	500	464	171	295	336	118	213
Percent of Total (%)		26.1	74.1		36.9	63.6		35.1	63.3
Settling Frequency (Hz)	59.79	59.79	59.79	59.66	59.66	59.66	59.54	59.55	59.56
NERC Frequency Response (MW/0.1Hz)	1272	1272	1271	794	795	791	590	592	606
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	1024	269	760	609	224	396	424	152	275
Percent of Total (%)		26.3	74.2		36.8	65.0		35.8	64.9

This case indicates that extremely depleted headroom will result in unacceptable system performance. The annotations in the right-hand figure reinforce the notion that Kt *alone* is insufficient to anticipate frequency performance, and that headroom should be considered – at least when it is in short supply. The performance metrics, shown in the three right hand columns of ***Table 5-6***, are consistent with unacceptable performance. The NERC frequency response was 590 MW/0.1 Hz, roughly equal to the minimum proposed FRO target of 548 MW/0.1 Hz. The

California settling based response is 152 MW/0.1Hz. It is worth noting that for this case in particular, the slow frequency recovery means that time or time window for which settling frequency is measured becomes quite important. Had the settling frequency assumed to be the average frequency between 20 and 52 seconds, these metrics would have been substantially worse.

5.2. POTENTIAL MITIGATION MEASURES

In this section, we examine possible means to improve frequency performance.

5.2.1. REDUCED GOVERNOR WITHDRAWAL

Causes and mitigation for poor frequency performance can be the obverse and reverse of the same issue. In this case, we examine the potential benefit of reducing the observed governor withdrawal, discussed in Section **3.5.2** To eliminate deliberate governor withdrawal, in this case the load control on the 18 units with lcfb1 model was disabled.

This case initial condition is the Wind Low Load – High WECC wind case with practical minimum (8GW) headroom (as shown in Section **5.1.3.2**). The results are shown in ***Figure 5-6*** and ***Table 5-7***. As expected, the load control has relatively small impact on the frequency nadir, since relatively little governor response is withdrawn by that time. But the settling frequency is significantly impacted. The NERC frequency response for this case was 995 MW/0.1hz. This improvement, compared to 794 MW/0.1 Hz for the reference case, shows that the withdrawal causes a 20% degradation in frequency response. It should be noted that had settling frequency been measured earlier (than at 60 seconds), the degradation would have looked less severe, in terms of the NERC frequency response metric.

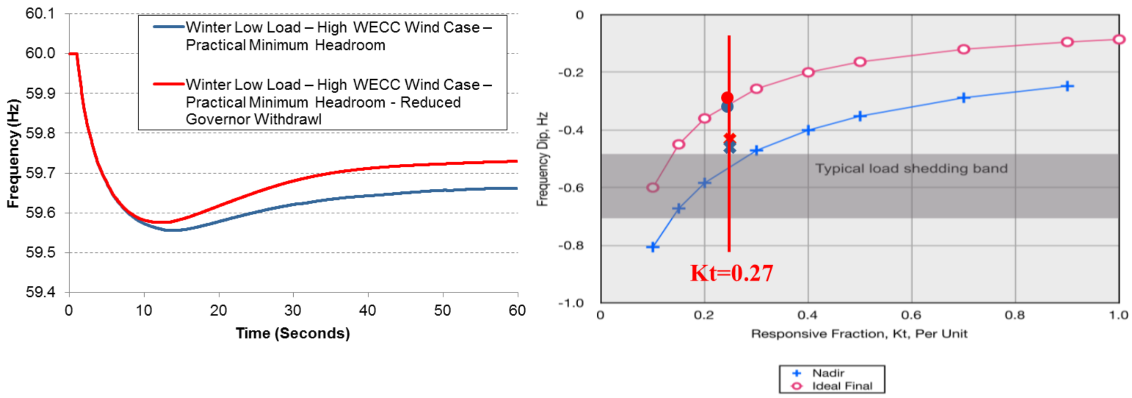

Figure 5-6 Impact of Reduced Governor Withdrawal on Frequency Performance for Winter Low Load – High WECC Wind Case

Table 5-7 Comparison of Performance Matrix of Reduced Governor Withdrawal

	Winter Low Load – High WECC Wind Case - Practical Minimum Headroom			**Winter Low Load – High WECC Wind Case – Practical Minimum Headroom – Reduced Governor Withdrawal**		
	WECC	**CA**	**Non-CA**	**WECC**	**CA**	**Non-CA**
Frequency Nadir (Hz)	59.56	59.55	59.55	59.58	59.57	59.57
Frequency Nadir Time (Seconds)	13.4	14.6	13.4	12.8	11.7	13.1
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	605	604	598	634	630	632
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	464	171	295	497	164	337
Percent of Total (%)		36.9	63.6		33.0	67.8
Settling Frequency (Hz)	59.66	59.66	59.66	59.73	59.73	59.73
NERC Frequency Response (MW/0.1Hz)	794	795	791	995	994	995
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	609	224	396	780	258	525
Percent of Total (%)		36.8	65.0		33.1	67.3

5.2.2. INERTIAL RESPONSE FROM WIND PLANTS

The initial conditions for this case was the Winter Low Load – High WECC Wind case presented in the previous section. In this sensitivity case, all of the type 3 wind turbines machines in the model, with a total power output of 14600 MW (out of a total of 18094 MW wind for the case) are assumed to have an inertial control based on the present GE offering [7].

The results are shown in ***Figure 5-7***. In comparison to the reference case, the inertial control arrests the frequency drop to some extent, and postpones the time of the frequency nadir. The power output of the type 3 machine is shown on the right. In the reference case, as expected, the power output is essentially unaffected by the disturbance. The inertial control rapidly increases the output, by about 500MW. This case points out one aspect of inertial controls for wind turbines: the energy "borrowed" from the stored inertial energy of the drive-train must be returned to the machine, including a "penalty" for time that the machines are running at sub-optimal speed and therefore reduced mechanical power capture. This "backswing" is responsible for the stretched out shape of the frequency recovery. In this case, the depth of the frequency nadir is reduced about 15mHz. With this high level of wind generation, the response of the wind inertial control is arguably too aggressive, since the recovery nearly causes a later frequency dip.

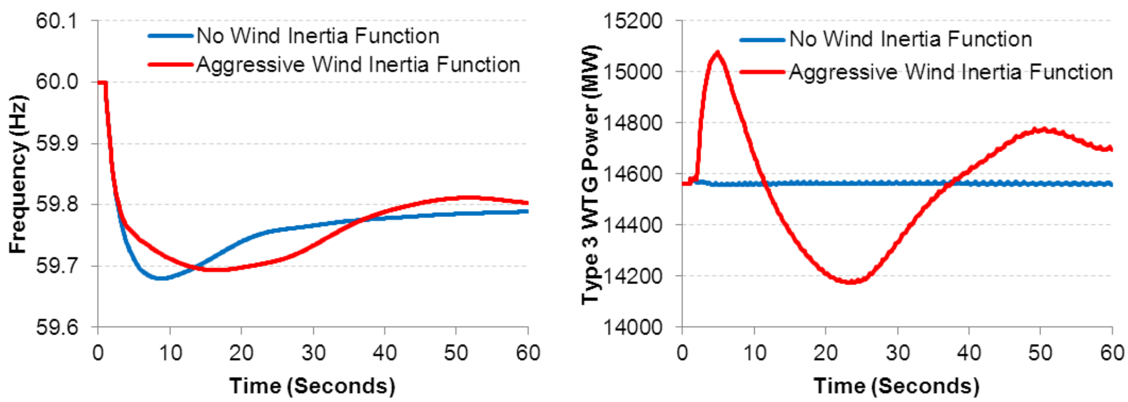

Figure 5-7 Impact of Wind Inertial Control on Frequency Performance for Winter Low Load – High WECC Wind case

In ***Figure 5-8***, a case in which the wind inertial control is tuned to be less aggressive is added. The result is both an improved frequency nadir, with about 20mHz of margin added, and a more orderly frequency recovery. The ability to tune these inertial controls presents an opportunity to improve system performance, but also adds a new dimension of planning uncertainty. Further tuning of this control might be expected to add another 10mHz or so onto the improvement here. Since wind inertial controls are relatively new, and not in widespread use, it is likely that further refinement of these controls will occur before the technology enters widespread use.

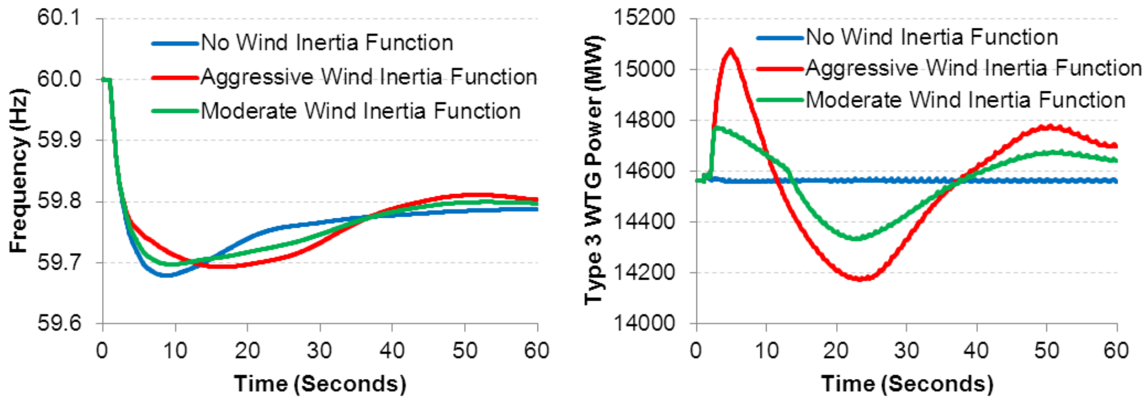

Figure 5-8 Impact of Various Wind Inertial Control Settings on Frequency Performance

In ***Figure 5-9***, we use the practical minimum headroom (8 GW headroom) initial condition presented in the previous section to further examine the potential benefit of inertial controls. The red trace and points on the right-hand figure are without the inertial control, and the green trace and points are with it. Here the frequency nadir is improved with the inertial control. The final frequency, at 60 seconds, is improved as well, but this isn't particular meaningful, as the frequency will ultimately settle at the same level since the inertial control cannot provide a sustained increase in power output. The frequency trace shows that, per the discussion in Section **2.2,** the final definition by NERC of settling frequency will strongly impact the calculated value of the frequency response metric. Ultimately this case illustrates a limitation of inertial controls: they have relatively little benefit for systems that have limited headroom. Other work [8] examining WECC under conditions of higher wind, but more generous headroom, showed much greater frequency benefits than are shown in these cases.

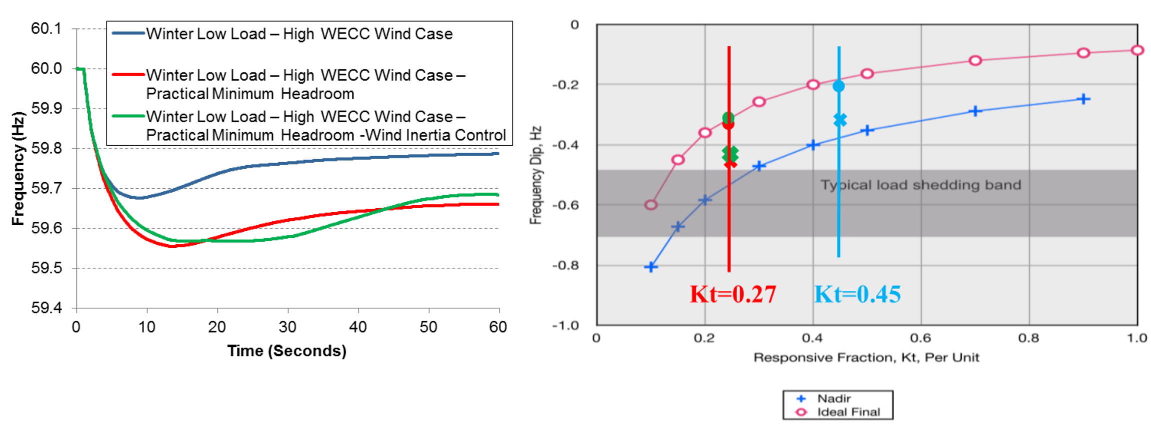

Figure 5-9 Comparison of Performance with Wind Inertial Controls

Table 5-8 Comparison of Performance Matrix of Wind Inertia Function for the Practical Minimum Headroom case

	Winter Low Load – High WECC Wind Case			Winter Low Load – High WECC Wind Case – Practical Minimum Headroom			Winter Low Load – High WECC Wind Case – Practical Minimum Headroom – Wind Inertia Control		
	WECC	CA	Non-CA	WECC	CA	Non-CA	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.68	59.68	59.68	59.56	59.55	59.55	59.57	59.57	59.57
Frequency Nadir Time (Seconds)	9.1	8.5	9.3	13.4	14.6	13.4	15.6	14.9	16.0
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	839	834	836	605	604	598	622	621	626
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	675	176	500	464	171	295	490	167	323
Percent of Total (%)		26.1	74.1		36.9	63.6		34.1	65.9
Settling Frequency (Hz)	59.79	59.79	59.79	59.66	59.66	59.66	59.68	59.68	59.68
NERC Frequency Response (MW/0.1Hz)	1272	1272	1271	794	795	791	853	853	841
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	1024	269	760	609	224	396	672	230	434
Percent of Total (%)		26.3	74.2		36.8	65.0		34.2	64.6

The impact of wind inertial controls on the Weekend Morning – High WECC Wind and Solar case is shown in ***Figure 5-10*** and summarized in ***Table 5-9***. The benefit in this case is greater, giving a roughly 20% improvement in the nadir-based frequency response metric. The point about the recovery and settling frequency applies here as well: The greatly improved NERC (60 second settling) metric is largely an artifact of measuring frequency at that specific time in the post-disturbance frequency swing. Other sliding window approaches would show different, and likely similar, performance metrics between the cases. Nevertheless, this case shows that inertial controls can give a significant benefit in terms of improving margin above UFLS, even for stressed conditions.

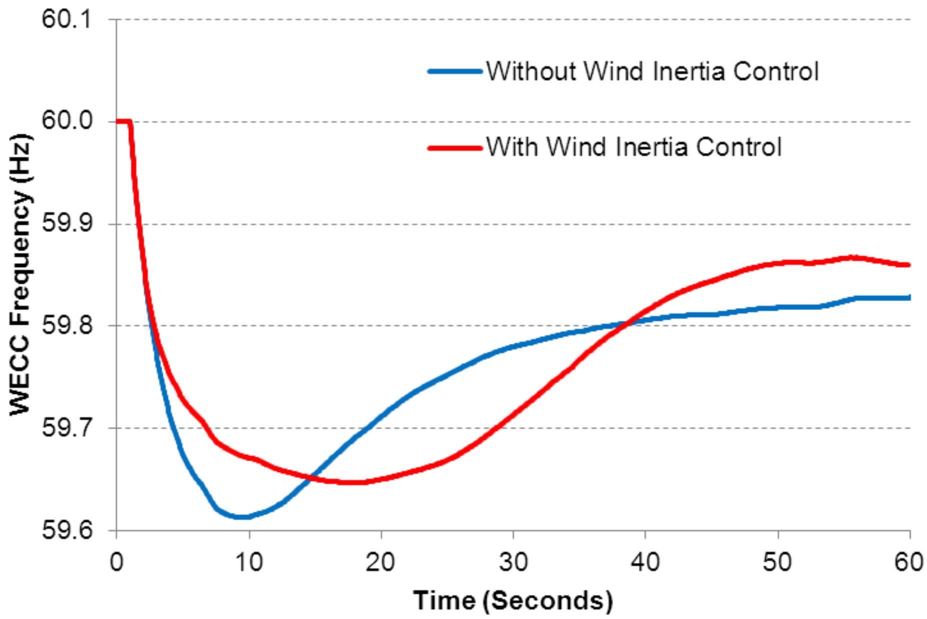

Figure 5-10 Impact of Wind Inertia on Frequency Response for Weekend Morning – High WECC Wind and Solar Case

Table 5-9 Performance Matrix for Weekend Morning – High WECC Wind and Solar Case, with and without Wind Inertia Function

	Weekend Morning – High WECC Wind and Solar Case			Weekend Morning – High WECC Wind and Solar Case – Wind Inertia		
	WECC	CA	Non-CA	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.61	59.61	59.61	59.65	59.65	59.65
Frequency Nadir Time (Seconds)	9.7	9.9	9.1	18.5	16.9	18.5
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	695	684	697	762	761	763
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	515	140	354	639	152	484
Percent of Total (%)		27.0	69.0		23.8	75.7
Settling Frequency (Hz)	59.83	59.82	59.83	59.86	59.85	59.86
NERC Frequency Response (MW/0.1Hz)	1565	1520	1578	1910	1845	1941
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	1158	311	802	1601	369	1232
Percent of Total (%)		26.9	69.3		23.0	77.0

5.2.3. GOVERNOR-LIKE RESPONSE (FREQUENCY DROOP) FROM WIND PLANTS

Under conditions of high stress that result in shortage of system Kt and headroom, wind generation can contribute to primary frequency response. In order to do so, the wind generators must be dispatched (curtailed) to power level less than that possible with the available wind speed. This results unrecoverable loss of energy production (much like spilled water on hydro generation), and so has significant economic implications.

The potential for wind generation to respond quickly makes this resource highly effective in arresting and correcting frequency deviations – much as very fast governor response on thermal generation.

In the test scenario presented here, we start with extremely low headroom case presented above in Section **5.1.3.3.** That case had unacceptable frequency response, due to an insufficient supply of primary response. In this first test case, a fraction of the wind generation in WECC is assumed to be operating slightly curtailed and with governor-like response enabled. Specifically, approximately 41% of all the WTGs in WECC are provided with standard 5% droop, 36mHz deadband governors. This condition adds a total of 1812 MW of headroom. The dynamic response of the wind governors is based on the present GE "frequency droop" control feature. A comparison of the cases is shown in ***Figure 5-11*** and summarized in ***Table 5-10***. The performance of this case is dramatically better. The frequency performance metrics for this case are better than the case that had about 12,000 MW more headroom from conventional machines (see ***Figure 4-1***). This case shows that, if necessary, primary frequency response from wind generation has the potential to greatly improve system frequency performance of the entire WECC grid. The California contribution to frequency response goes from an unacceptable 152 MW/0.1 Hz to a healthy 258 MW/0.1 Hz.

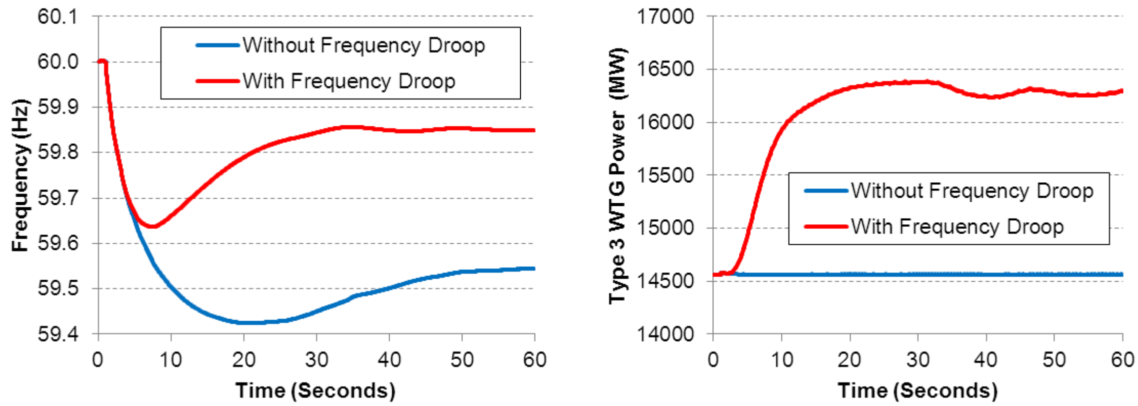

Figure 5-11 Impact of Frequency Droop Function on Frequency Performance for Winter Low Load – High WECC Wind– Extreme Minimum Headroom case

Table 5-10 Performance Matrix for Winter Low Load – High WECC Wind Case – Extreme Minimum Headroom, with and without Frequency Droop Function

	Winter Low Load – High WECC Wind Case – Extreme Minimum Headroom			Winter Low Load – High WECC Wind Case – Extreme Minimum Headroom – Frequency Droop		
	WECC	CA	Non-CA	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.42	59.42	59.43	59.64	59.63	59.63
Frequency Nadir Time (Seconds)	20.7	18.8	20.7	7.4	8.3	7.2
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	467	461	468	739	736	727
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	336	118	213	538	106	415
Percent of Total (%)		35.1	63.3		19.3	77.5
Settling Frequency (Hz)	59.54	59.55	59.56	59.85	59.85	59.85
NERC Frequency Response (MW/0.1Hz)	590	592	606	1787	1794	1793
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	424	152	275	1301	258	1036
Percent of Total (%)		35.8	64.9		19.8	79.6

A further investigation of governor-like controls for wind turbines was done on the Weekend Morning – High WECC Wind and Solar Case. Approximately 59% of all the Wind Turbine Generators (WTGs) in WECC were provided with standard 5% droop, 36mHz deadband governors. This condition adds a total of 3447 MW of headroom. Again, the performance, in terms of both frequency nadir and settling frequency, is greatly improved. The recovery is stable and well mannered: 3447 MW of Wind headroom is worth much more than an equivalent amount from the existing synchronous generation as dispatched in these cases. Specific individual generating units with fast responding governors could likely provide similar benefits on per MW basis.

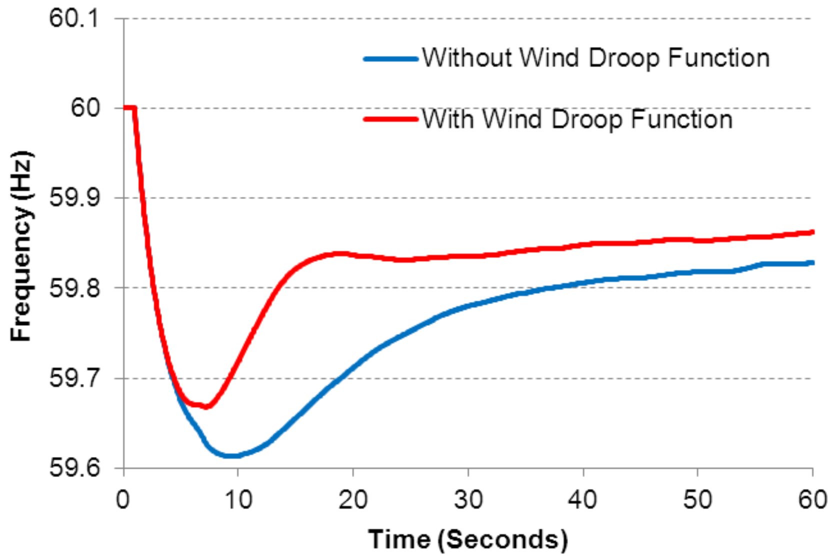

Figure 5-12 Impact of Frequency Droop on Frequency Response to Loss of Two Palo Verde Units, for Weekend Morning – High WECC Wind and Solar Case

.

Table 5-11 Performance Matrix to Loss of Two Palo Verde Units for Weekend Morning – High WECC Wind and Solar Case, with and without Frequency Droop Function

	Weekend Morning – High WECC Wind and Solar Case			Weekend Morning – High WECC Wind and Solar Case – Frequency Droop		
	WECC	CA	Non-CA	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.61	59.61	59.61	59.67	59.65	59.67
Frequency Nadir Time (Seconds)	9.7	9.9	9.1	7.2	5.7	7.2
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	695	684	697	810	770	815
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	515	140	354	629	99	519
Percent of Total (%)		27.0	68.7		15.7	82.5
Settling Frequency (Hz)	59.83	59.82	59.83	59.86	59.86	59.86
NERC Frequency Response (MW/0.1Hz)	1565	1520	1578	1947	1881	1921
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	1158	311	802	1510	243	1257
Percent of Total (%)		27.0	69.0		16.1	83.3

In the case shown in ***Figure 5-13*** and summarized in ***Table 5-12***, the impact of having *all* wind generation in WECC providing frequency droop is shown. This case is only approximate, in that we have increased the gain on some of the wind turbines in order to approximate having all the wind turbines in WECC active with 5% droop. But all the responsive wind turbines are outside of California. The two performance metrics are very good, showing even more improvement than the previous case. However, notice that the high gain controllers have introduced a degree of overshoot on the first frequency swing, followed by rather slow oscillations (about 15 second period, or 0.071Hz). These oscillations are well damped, nevertheless, at high levels of wind penetration, the transient response of the wind turbines might need to be slowed. The key point is that the speed of response of wind turbine governor controls can be tuned to a greater extent than that of most synchronous generation. This can result in better system performance. But the addition of new control elements to the power system requires care to avoid unintended consequences. This is consistent with NERC recommendations.

Another point is potentially important here. The recovery in this case, with new high response wind governors outside of California, makes the performance of California resources look less good. Some care is needed to avoid situations where California with adequate performance is penalized because performance of resources outside of California (or the BA) is particularly good.

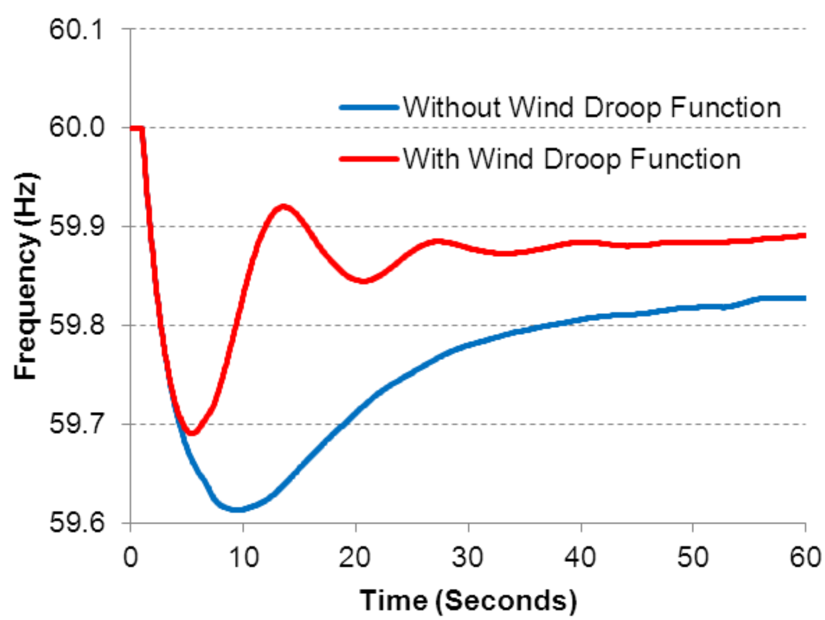

Figure 5-13 Performance Matrix to Loss of Two Palo Verde Units for Weekend Morning – High WECC Wind and Solar Case, with and without Frequency Droop Function

Table 5-12 Performance Matrix to Loss of Two Palo Verde Units for Weekend Morning – High WECC Wind and Solar Case, with and without Frequency Droop Function

	Weekend Morning – High WECC Wind and Solar Case			Weekend Morning – High WECC Wind and Solar Case – Frequency Droop		
	WECC	CA	Non-CA	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.61	59.61	59.61	59.69	59.67	59.67
Frequency Nadir Time (Seconds)	9.7	9.9	9.1	5.4	5.6	5.6
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	695	684	697	870	813	838
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	515	140	354	536	104	423
Percent of Total (%)		27.0	68.7		19.4	78.9
Settling Frequency (Hz)	59.83	59.82	59.83	59.89	59.89	59.89
NERC Frequency Response (MW/0.1Hz)	1565	1520	1578	2471	2365	2365
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	1158	311	802	1522	302	1232
Percent of Total (%)		27.0	69.0		19.8	81.0

5.2.3.1. MECHANICAL IMPACTS OF ACTIVE POWER CONTROLS ON WIND TURBINES

The fact that variable speed WTGs (i.e. basically all that are being built now) have power electronics that can change torque more-or-less instantaneously, enables the performance shown in the last two sections. Manipulating torque has implications for mechanical stresses on the wind turbines, as these torque changes are reflected on the generator, the drive-train and the rest of the wind turbine mechanical systems (blades, tower, nacelle). Indeed, during grid faults, the massive step in torque is a critical design consideration -- just as it is with all other types of generation. Violent torque events do have loss-of-life considerations. So, having control actions that might contribute to loss-of-life through overly aggressive torque action is a legitimate concern. For example, it would be possible to have a frequency sensitive control (inertial control or governor-like control) that imposed a massive step change in torque. Per the discussion in Section **5.2.4** (below), waiting until the frequency decays then suddenly injecting massive power can be effective -- but would likely have an adverse impact on the life WTGs.

However, since this is all "control", the turbine designers have the ability to manage/limit the torque impacts. It is incumbent on the WTG Original Equipment Manufacturer (OEM) to take into account these design limits. The controls used in this analysis were the subject of extensive design review, testing and due diligence, specifically so that having these controls will not result in significant loss-of-life. This is critical to adaptation of such controls by the industry. It is incumbent on the OEMs to set limits on how aggressive the controls can be; leaving system studies that might result in reducing the aggressiveness up to grid planners. The capabilities of the turbines modeled here are generally at the point where the dynamic response is as good or better than that of the synchronous fleet.

Adaptation of these new controls with respect to grid requirements requires some reasonable judgment: Ask that the WTGs do as much as they can without damaging themselves, or driving significant costs into the turbines. This last point, which ought to be obvious, is made because there are places (not WECC) where people are demanding speed of response considerably in excess of what is possible with the existing synchronous fleet. Such requirements, without consideration of practical limitations of the mechanical impacts on the turbines, are inappropriate.

5.2.4. LOAD CONTROL/FAST ENERGY STORAGE

The unacceptable performance of the case with extremely reduced headroom presents an opportunity to test non-generation options for mitigation. Clearly, one criterion for satisfactory performance is the avoidance of involuntary under-frequency load shedding. However, the voluntary (and presumably compensated) participation of loads in managing frequency presents an opportunity to bring technically and cost effective non-generation resources to bear on the frequency control problem.

California has many large pumping loads. These loads are important to the dynamics of WECC and are explicitly modeled. Rapid disconnection of these loads on under-frequency (and for other systemic needs) has long been practiced in California. In the current system model, the most aggressive tripping of these loads on under-frequency occurs at or below our target frequency of 59.5 Hz.

In the test case presented here, we have enabled UFLS on the explicitly modeled pumps and pumped storage hydro plants. We have raised the tripping threshold to 59.7 Hz – above the present setting. Notations in the data set suggest that at least some of these pump loads had UFLS settings at this frequency in the past. It is not certain whether the changed data is because settings were changed or for some other reason.

The frequency response of this case, compared to the reference case, is shown in ***Figure 5-14*** and the metrics are summarized in ***Table 5-13***. Tripping of 1379 MW of pump motor load immediately arrests the frequency decline. The performance is excellent, and the performance metrics are such that this level of load response is equivalent in this case to having roughly an order of magnitude more generation headroom. It is even more effective than the governor response from the wind turbines.

This raises some interesting points: clearly this resource is highly non-linear. Such performance would likely be impossible with a linear proportional control, like governor droop: The equivalent gain would be too high to be stable. So, the contribution of the load resources with these uniform settings is bi-modal: For a smaller disturbance, the load wouldn't have tripped and the contribution to California's frequency performance would have been nil. And yet, the most important consideration is, arguably, to stay away from involuntary UFLS. This resource is highly effective in doing so: under conditions of high stress (low headroom, low Kt), higher frequency (~59.7) tripping of 1379 MW pump motor load was "worth" approximately 0.2 of Kt and/or 12 GW headroom). Conversely, it is difficult to believe that the system performance could be made robust if too large a fraction of the total frequency response were to come from this type of resource.

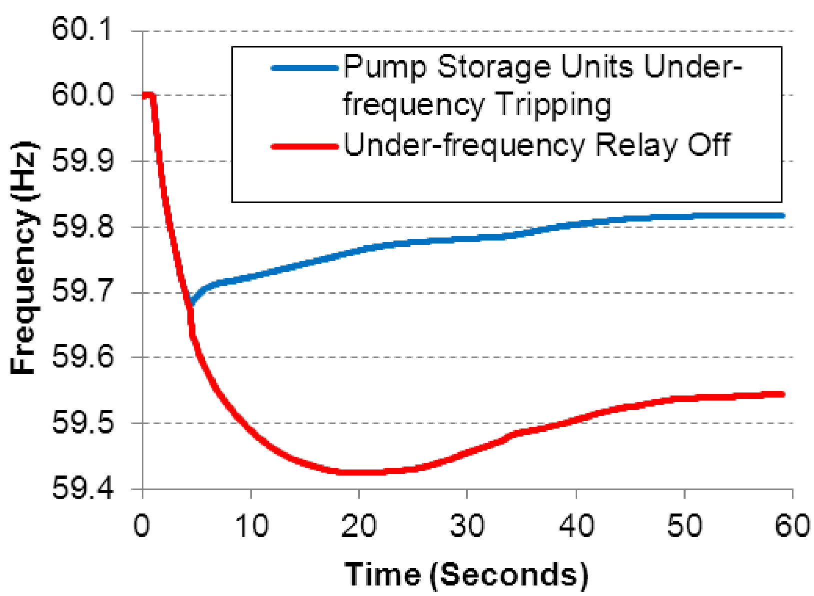

Figure 5-14 Impact of Pump Storage Units Under-frequency Tripping on Frequency Performance

Table 5-13 Performance Matrix to Loss of Two Palo Verde Units for Winter Low Load – High WECC Wind Case, with and without Pump Storage Units Under-frequency Tripping

	Winter Low Load – High WECC Wind Case – Extreme Minimum Headroom			Winter Low Load – High WECC Wind Case – Extreme Minimum Headroom – Pump Storage Units Under-frequency Tripping		
	WECC	CA	Non-CA	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.42	59.42	59.43	59.68	59.68	59.68
Frequency Nadir Time (Seconds)	20.7	18.8	20.7	4.6	4.6	4.6
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	467	461	468	847	843	844
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	336	118	213	349	301	46
Percent of Total (%)		35.1	63.3		86.2	13.1
Settling Frequency (Hz)	59.54	59.55	59.56	59.82	59.82	59.82
NERC Frequency Response (MW/0.1Hz)	590	592	606	1471	1475	1474
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	424	152	275	607	527	81
Percent of Total (%)		35.8	64.9		86.8	13.3

The results of this case shed light on the potential for other fast acting resources to aid in frequency response. For example, fast acting energy storage, with appropriate frequency sensitive controls would clearly be useful in arresting frequency decline. Flywheel or battery systems could be engineered to rapidly inject power to help arrest and correct frequency decline. This case shows how roughly 1300MW of a fast injecting resource might help. More refined controls could be (and have been) designed for energy storage devices to help with frequency response. It is fair to say that these resources, because of their potentially greater speed, would provide more benefit on a per-MW basis than headroom in the "representative" fleet in WECC. None of the results in this study indicate, as some have suggested, that the system *must* have energy storage devices to accommodate high wind and solar conditions. But, they would be valuable, and sending the right economic signals to encourage *all* frequency response resources for better, i.e. faster, response, would seem to be an appropriate technology neutral means of achieving the best balance of reliability and cost.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

- **Frequency Response is not in crisis for California.** No credible conditions examined, even with quite high levels of wind and solar (up to 50% penetration in California), resulted in under-frequency load shedding or other stability problems.
- **Secondary reserves need to be adequate.** The study assumes that sufficient secondary reserves (regulation and load following) are generally available to handle the variability of wind and PV generation. However, if secondary reserves are exhausted due to wind, solar or load variability, then primary frequency controls may act if the frequency changes significantly. This will result in reduced primary frequency response capability for responding to faults. Conditions of greatly reduced headroom were examined in this study, but causal links to the variability of wind and solar generation on availability of frequency response was not considered in this analysis. Dispatch and unit commitment in base cases was set by the CAISO, and was based on real operating history and practice. This will inevitably change.
- **No UFLS action in the Base Case Simulations.** All the CAISO Base Cases perform well. None of the 4 base conditions with high wind and solar in California result in under-frequency load shedding for design basis events simulated in this study.
- **Renewable penetration outside of California is important.** With non-CA WECC operating with higher wind, overall performance can degrade, although this is not always observed. Good response outside of CA improves overall system performance – benefiting California. Cases with added wind in non-CA WECC, for total WECC-wide of 19% instantaneous wind (21.9 % wind and solar) result in compliant frequency response
- **California's response generally meets its FRO depending on system conditions.** The new draft NERC frequency response obligation (FRO), , assigns an obligation to each entity/BA to provide a minimum level of frequency response. That obligation is set in accordance with the size of the BA, as measured by the peak load and generation. In [1], a WECC-wide target of 685 MW/0.1 Hz is proposed, a 30% share of this assigned to California would be 205 MW/0.1Hz. In this report, the frequency response of California is reported at 60 seconds, in MW and in percentage of the total provided by all generation in WECC, for each case. Typically, that response was in the neighborhood of 250 MW/0.1Hz and 30% of

the WECC total. The range for successful cases (i.e. those that did not cause UFLS) was 224 to 369 MW/0.1Hz, and 20 to 39% of WECC total. At the low end of these ranges, it is possible that California (and therefore CAISO) might not meet the NERC FRO.

- **Kt is a good primary metric.** Kt , the fraction of generators providing governor response, is a good, relatively simple metric that gives considerable insight into the system's ability to provide adequate frequency response. Reduction of headroom to 8GW (with the fraction of generators providing governor response, "Kt" ≈ 0.25) results in compliant response; Further reduction in headroom to 3GW (even with "Kt" ≈ 0.25) results in UFLS action (if no other mitigation is added). Based on the cases run in this study, the lower limit of 0.30 suggested by LBNL work *may* be a little conservative. Our results suggest that 0.25 may be enough.
- **Kt alone does not give all the necessary information… headroom is important.** In particular, headroom is important, *if it is in short supply:* For example, a high wind and solar condition with a total available headroom ≈ 9% WECC load *and* Kt ≈ 0.25, results in satisfactory performance that avoids UFLS. In this case, the ratio of headroom to event size is ~ 8000/2690 ≈ 3:1. However, with Kt still at ≈ 0.25, but headroom shrunk to ≈ 3% WECC load (Headroom: Event size ≈ 1:1), performance results in UFLS, without other mitigation. This suggests that, when conventional synchronous generation of "representative" speed of response is providing the majority of frequency response, a ratio of about 3:1, headroom to limiting event, *on a system-wide basis* (not on the basis of individual entities/BA) should give adequate performance. It should be noted that we see no evidence to suggest that the system would deliberately be operated at lower levels of headroom, such as the 1:1 condition tested. Whether such an extreme condition could occur as a possible consequence of an extreme wind/solar forecast error warrants further investigation. The WWSIS work [6] found that on occasions extreme forecast errors could impinge on the on-line portion of contingency reserves. This is a risk addressed in WECC operating guidelines with respect to load variation. It is a concern raised by the FERC LNBL reports [3,5]
- **Speed of primary response is important.** Faster governors have a significant impact on the frequency nadir. This could be taken into consideration during procurement of primary response - – less MW of headroom with faster response can give the same margin above UFLS thresholds. 5% droop means that substantial headroom (i.e. greater than 10-15% of rating) on individual

generators is largely useless, since frequencies must drop below UFLS thresholds for the governor to increase output more than about 13% of rating.

- **Governor Withdrawal has a detrimental impact on frequency response.** The dynamic model for WECC includes many units with load control functions that cause them to withdraw frequency response while the system frequency is still depressed. Detailed examination of one case showed that 18 committed governor responsive machines had some degree of withdrawal. This caused a roughly 20% degradation (794 MW/0.1 Hz vs. 995 MW/0.1 Hz without this withdrawal) in frequency response (at 60 seconds). This caused a 4% degradation in the nadir-based frequency response (i.e. a somewhat more extreme frequency excursion).
- **Impact of reduced System Inertia on initial rate-of-change-of-frequency does not appear to be important.** Tests to look at the impact of change in system inertia alone (i.e. all other aspects being held essentially equal) show some impacts on the initial rate-of-change-of-frequency (ROCOF). However, higher initial ROCOF has relatively little impact on the severity of the frequency excursion, and none on the settling frequency. This is consistent with the LBNL Report. However…
- **Inertial controls from Wind Generation help.** Or more precisely providing fast transient support, via controlled inertial response from wind turbines – at least of the type provided by GE WindINERTIA – can significantly improve the system frequency nadir (≈ + 5% or more). This is particularly the case if the frequency nadir is significantly lower than the settling frequency, which tends to be the case if the system is not short of Kt and headroom. This means that these types of controls can reduce the need to worry about the *speed* of individual unit governor response, but they do relatively little to correct a shortage in the *amount* of available response. Under normal conditions, these controls will add margin in avoiding under-frequency load shedding.
- **Results are largely consistent with LBNL predictions.** Actual frequency nadirs in our simulations are somewhat better than in the simple illustrative cases provided by John Undrill in the LBNL report. The settling frequencies are somewhat worse, and are significantly impacted by governor withdrawal, which is also consistent with FERC and NERC concerns.
- **Participation of renewables in providing frequency response is beneficial**. Unlike inertial response, wind plant frequency response, i.e., governor-like

controls, will have significant beneficial impact on *both* frequency nadir and settling frequency, thereby helping to meet FRO obligations. This should prove valuable under conditions when the system is short of Kt or headroom. To provide this function, wind plants must be dispatched below available wind power, causing an opportunity cost equal to the lost production (like spilling water over a hydro dam). Since the controls can be quite fast relative to conventional thermal and hydro generation, the benefit is greater. For example, in the test case, provision of about 1800 MW wind headroom results in approximate same benefit as ~12000 MW of conventional generation headroom: a 7:1 benefit. This is because the response is much faster than the average contribution of the synchronous governors re-dispatched in this study. Other types of generation may be able to provide comparable benefits, if tuned to do so. Providing the governor-like function when wind plants are curtailed for other reasons (e.g. thermal congestion), should be valuable as well.

At high levels of wind governor-like participation, 5% droop represents a high transient gain, since wind plants can be much faster than conventional plant governors. Experiments with even higher transient gains started to show significant oscillations, as might be expected from any very high gain governor. At very high levels of wind penetration it is possible that wind plant governor functions, when enabled, will need to be slowed down to be closer to conventional synchronous plants.

- **Load control can be used to improve frequency response.** In the test case, tripping of California pumping loads and PSH at higher frequency (~59.7 Hz), under conditions of high stress (low headroom, low Kt), is highly effective in reducing the severity of the frequency nadir and raising the settling frequency. Specifically, 1379 MW of load tripped at 59.7 Hz, was worth approx. 0.2 of Kt and/or 12,000 MW of headroom.
- **Fast acting Energy Storage will provide significant benefits.** Benefit of fast response (on a per MW basis) in minimizing frequency nadir is substantial. These results suggest that extremely fast resources (energy storage, load response, etc.) will have a 1:1 benefit (relative to the size of the limiting event). This further suggests that fast energy devices *dedicated to providing primary frequency response,* will be worth *roughly* three times that of the average synchronous machine re-dispatched in this study in terms of their impact on frequency nadir.

6.2. RECOMMENDATIONS

As noted in the conclusions, the results of this study indicate that frequency response, while not in evident danger of causing significant reliability concerns for CAISO, warrants attention. The following recommendations are aimed at positioning the CAISO (and the WECC) to avoid frequency response concerns from becoming a serious problem. We have grouped the recommendations in four general categories: (1) Investigative Studies, (2) Planning and interconnection related changes, (3) Market changes and (4) Operational changes.

6.2.1. INVESTIGATIVE STUDIES

- **Investigate causes and evaluate possible technical remedies for low participation in frequency control by the existing fleet.** Less than one third of committed generation in California contributes towards primary frequency response under some credible operating conditions. There are likely technical, economic and historical reasons for this. However, it is possible that specific plants which presently do not participate could do so with relatively little adverse consequence. A first step towards remedy would be to investigate and inventory the reasons for non-participation by every generator, including QFs and other participants not directly under CAISO control or jurisdiction
- **Investigate causes and mitigation of governor withdrawal.** Withdrawal of primary response while system frequency is depressed exacerbates frequency response concerns. This behavior is technically irresponsible and difficult to justify economically. CAISO should consider implementing rules that prohibit withdrawal when system frequency is depressed below a specified threshold. The threshold (or some functionally similar mechanism) should be coordinated with governor deadbands, ACE tolerances and other thresholds to avoid unintended interactions.
- **Investigate/calibrate available WECC stability models with recent frequency events.** It is necessary to have simulation models that can adequately predict the system frequency response. WECC has some of the best dynamic model verification practices anywhere in the industry, thus there is no fundamental reason to disbelieve the dynamic models used by CAISO (and in this study). Nevertheless, there is some *anecdotal* evidence that generators may be operating differently, e.g. with governors disabled and/or with load controls

enabled that defeat governor response. Detailed investigation of performance of individual units in response to actual grid events is recommended.

- **Investigate/calibrate available WECC load flow models for evaluation of possible frequency events.** As noted in the previous bullet, it is necessary to have simulation models that can adequately predict the system frequency response. As wind and solar generation increase in California and throughout WECC, patterns of unit commitment and dispatch will substantially depart from historical practice. Dynamic simulations of frequency events are only as good as the initial conditions. Therefore, it is critically important that these conditions realistically represent commitment and dispatch that would occur under conditions of particular concern, i.e. periods of high wind and solar, relatively low load, possibly high inter-area exchanges and poor wind and solar forecasts. Mechanisms to strengthen the ties between market/operational reality and planning models are needed and are under-development.
- **Investigate impacts, tuning and possible optimization of control on renewables for providing frequency response**. Wind plant controls for frequency response, both inertial controls and governor-like controls are not in widespread use. They offer speed and flexibility, as well as constraints, that are different from synchronous generation. Further investigation of the best way to take advantage of these functions is warranted.,
- **Quantify costs for sub-economic operations to meet frequency response requirements.** In the absence of market mechanisms to assure adequate frequency response, CAISO will inevitably be forced to adopt defensive operational strategies. These could have adverse consequences that might include preferential, out-of-merit, commitment and dispatch of responsive generation, curtailment of wind and solar generation, possible abrogation of power purchase agreements and fines levied against the CAISO for reliability violations. Estimation of such costs could be made with properly designed production simulations.
- **Develop system capability metrics for operations.** This study showed that Kt and headroom are important means of measuring the system's ability to meet frequency response objectives. The cases examined suggest that minimum targets of 0.25 and 8000MW (for all of WECC), respectively, might be adequate. However, this work cannot be considered exhaustive or definitive, and further investigation is certainly warranted. Also, other capability metrics may be

valuable, including speed of response, the physical location of resources providing response, or transient contribution to arresting frequency decline. Nuances such as differentiation of when there is “too much” on some units to be useful (e.g. >13% headroom with 5% droop), may need to be considered.

- **Track Evolving NERC FRO and ability of CAISO to meet it.** At this point, it appears that CAISO is not in violation of proposed NERC frequency response obligation; certainly the system has some frequency margin above UFLS. However, it appears that under some conditions, most notably the weekend morning condition, California is pushing limits. CAISO should continue to be engaged with the NERC and broader industry discussions around FRO, and continue to study whether CAISO can meet these obligations under credible operating conditions.

  Verify the availability of headroom in future studies: The study did not specifically address how headroom is obtained or accounted for in system operations. There are various ancillary services and related metrics that are regularly procured, or at least racked. These include various reserve products that include:

  - Contingency reserve
  - Spinning reserve
  - Regulation

  These reserve products alone may not assure adequate headroom.

6.2.2. PLANNING AND INTERCONNECTION RELATED CHANGES

Consider expansion of grid code/interconnection requirement to force all generation, including renewables *to be able to* participate in frequency response. The issue of frequency response, and the decline observed by NERC is NOT caused by wind and solar: at times two-thirds of committed generation doesn’t provide frequency response. Nevertheless, it makes sense for CAISO to have the option to take advantage of the potential for wind (at least) to provide fast, and therefore more valuable, primary response. This will contribute to system security, and should help to make any market structures for frequency response more liquid. From an engineering perspective, caution must be exercised to avoid unintended dynamic problems, such as poorly damped inter-area oscillations, that could result from large concentrations of very fast governors in wind-rich areas.

6.2.3. MARKET CHANGES

Investigate market mechanisms to ensure adequate frequency response. As mentioned earlier, operational tools to forecast primary frequency response requirement in addition to regulation and ramping requirements will greatly improve the reliability of the system. However, market and operational mechanisms are required to ensure that the forecasted primary frequency response is available in operations. Once forecasted, adequate frequency response can be ensured in a number of ways; for example, through the use of frequency response must run units under certain load and renewable generation conditions, through the use of a frequency response constraint in the unit commitment process. It might also be possible to have a market for frequency response where generators can offer their capacity into this market much like regulation. A market should reward fast, sustained frequency response.

Consider incenting inertial response from non-synchronous generation. Provision of inertial response controls on wind turbines, at least of the type examined in this study, does not displace the requirement for primary frequency response. However, it does tend to reduce the severity of frequency nadirs, and it reduces the need for governor response to be fast. Since the proposed NERC rules will evaluate response in the time period *after* the frequency nadir (e.g. 20-52 seconds), provision of inertial response on wind turbines will compliment frequency response measured this way. It will tend to reduce the need for more complex market signals rewarding fast response. A blanket requirement for inertial response may prove punitive for some technologies (e.g. this is very difficult and expensive for PV), and should be avoided.

Expand load response. Fast, voluntary disconnection of loads is highly effective in helping to arrest and recover from severe frequency events. Response during the pre-nadir period can greatly improve system response. Load response tends to be discrete, and therefore its contribution to linear metrics such as MW/0.1Hz will be poor for smaller events. Historical bias against voluntary use of demand-side resources will likely prove to be significantly uneconomic in high wind and solar futures for California and the WECC. More aggressive (than present practice) disconnection of known, discrete pumping loads in California was shown to be effective. CAISO should pursue participation by these and other loads. Design of possible market mechanisms to assure adequate frequency response should include mechanisms to encourage demand-side participation.

Allow energy storage to participate. Properly designed and controlled energy storage devices can provide similar benefits to those demonstrated in this study from load response and frequency control by wind turbines. Design of market mechanisms to assure adequate frequency response should include features to allow provision of frequency response by energy storage devices with finite (limited) energy ratings.

Allow a portion of a balancing area's FRO to be located outside the area. Challenge possible requirements for all frequency response obligations to be met with resources within California. The need for primary reserves to be distributed according to geographic constraints, as proposed in the FRO, was not shown to be very important in the cases examined in this study. As long as the entire system (i.e. all of WECC) has adequate primary reserves, strict adherence by individual entities, including CAISO, to the FRO was not shown by this work to be necessary. This aspect of FRO needs further investigation. These results suggest that it is likely that some portion (e.g. 25%) of each BA's FRO could be obtained from neighboring systems without adversely impacting system reliability. Impacts on system stability, particularly risks of causing or exacerbating system separation following large disturbances, would need to be evaluated (presumably on a case-by-case basis). Both market and accounting/monitoring mechanisms should be designed to consider the possibility of procurement of some frequency response from outside the CAISO. This is important and represents an equity issue: even though it is technically acceptable to have a portion of the FRO outside the BA, no one BA should provide FRO to another BA without compensation.

Consider mechanisms to assign costs for sub-economic operation to non-participating generation. This could be an alternative to creating market mechanisms to reward resources for providing primary frequency response. The up to 2/3 of generation that does not participate in primary frequency response is arguably the cause of sub-economic operation, and could be assigned a charge to defray the associated costs. This is, in the opinion of the authors, a blunt policy instrument compared to a properly designed market.

6.2.4. OPERATIONAL CHANGES

- **Evaluate present operator tools for determining adequacy of frequency response**. This study did not include any investigation of operational tools. However, these results suggest that it is important for CAISO operators to have good information about the count, rating and available headroom of committed units with active governors. The study performed by LBNL has proposed the use of primary frequency response as a leading metric[1] to establish whether primary frequency control reserves are capable of preventing the interruption of electric service to customers following the sudden loss of generation. Recently, the CAISO already has implemented tools to forecast regulation and ramping requirements for operations. Given the close interaction between secondary and primary reserves, it behooves CAISO to evaluate tools for determining the required primary frequency response and along with regulation and ramping. Tools to track and perhaps predict crucial capability and performance metrics will be needed.

[1] Primary frequency response metric is actually a series of metrics that describe the total power delivered by primary frequency control reserves at specific points in time following the sudden loss of a conventional generator. As system inertia changes, based on both the amount of conventional and variable renewable generation that is on line, the rate (or speed) of frequency decline can then be estimated (through simulation studies) for the assumed amount of conventional generation loss that the interconnection is expected to withstand. Coupled with knowledge of highest set point for under-frequency load shedding, the amount of primary frequency control required to arrest frequency above this set point can then be determined. The amount of primary control can then be expressed using the primary frequency response metrics to establish the performance requirements for the minimum amount of power expected from primary frequency control reserves at each point in time.

7. ACKNOWLEDGEMENTS

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APPENDIX A. KEY TO ACRONYMS

ACE	Area Control Error
AGC	Automatic Generation Control
BA	Balancing Authority
COI	California Oregon Intetie
FERC	Federal Energy Regulatory Commission
FRO	Frequency Response Obligation
IEEE	Institute of Electrical and Electronics Engineers
LBNL	Lawrence Berkeley National Lab
LF	Load Following
MAPS	Multi-Area Production Simulation
NERC	North American Electric Reliability Council
PFR	Primary Frequency Response
PSH	Pumped Storage Hydro
ROCOF	Rate of Change of Frequency
SCIT	Southern California Import Transmission
UFLS	Under Frequency load Shedding
WECC	Western Electricity Coordinating council
WOR	West of River
WTG	Wind Turbine Generator
WWSIS	Western Wind and Solar Integration Study

APPENDIX B. DETAILED SIMULATION PLOTS

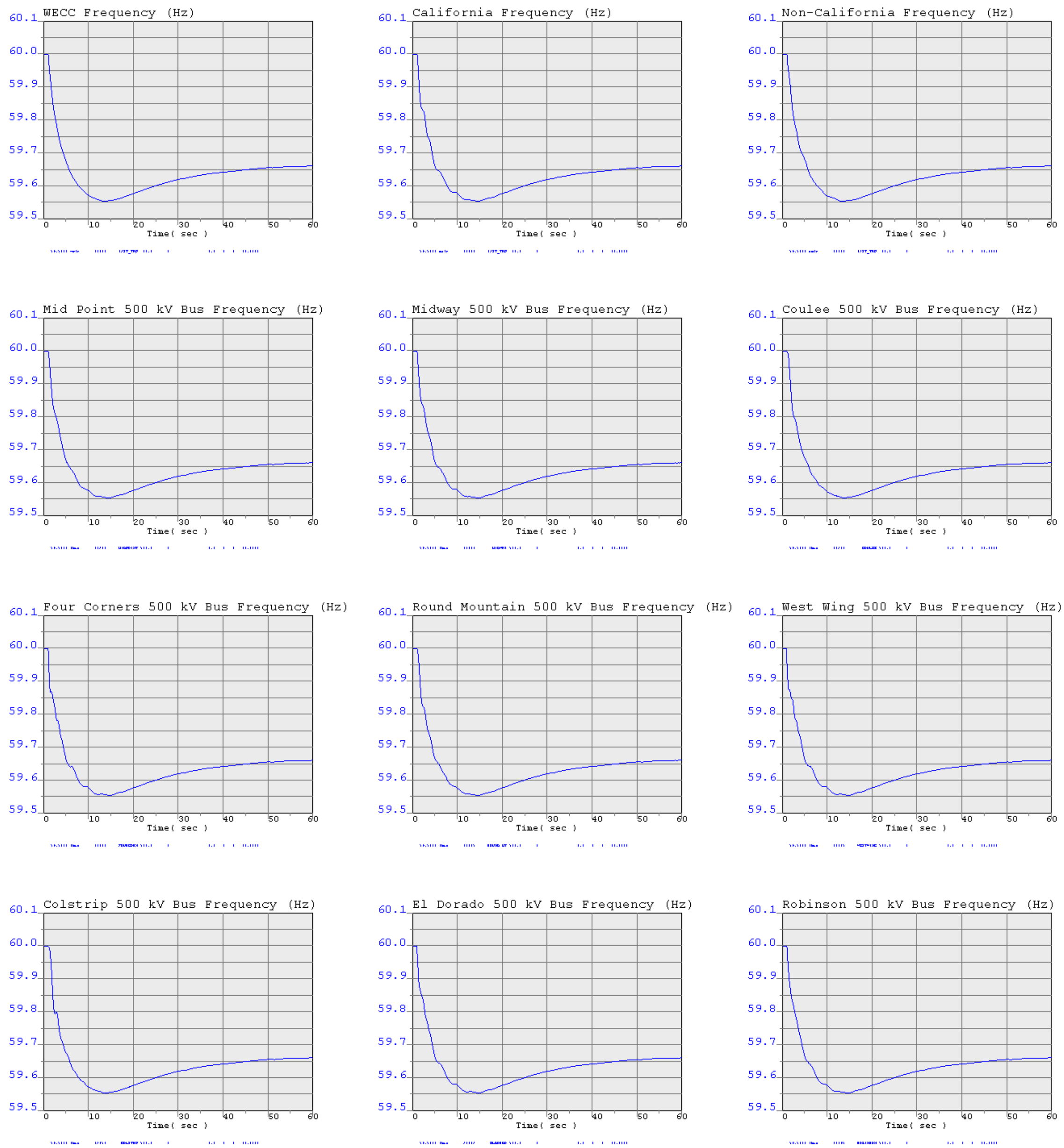

Figure A1 Frequency Behavior to Loss of Two Palo Verde Units for Winter Low Load – High WECC Wind Case - Practical Minimum Spinning Reserves

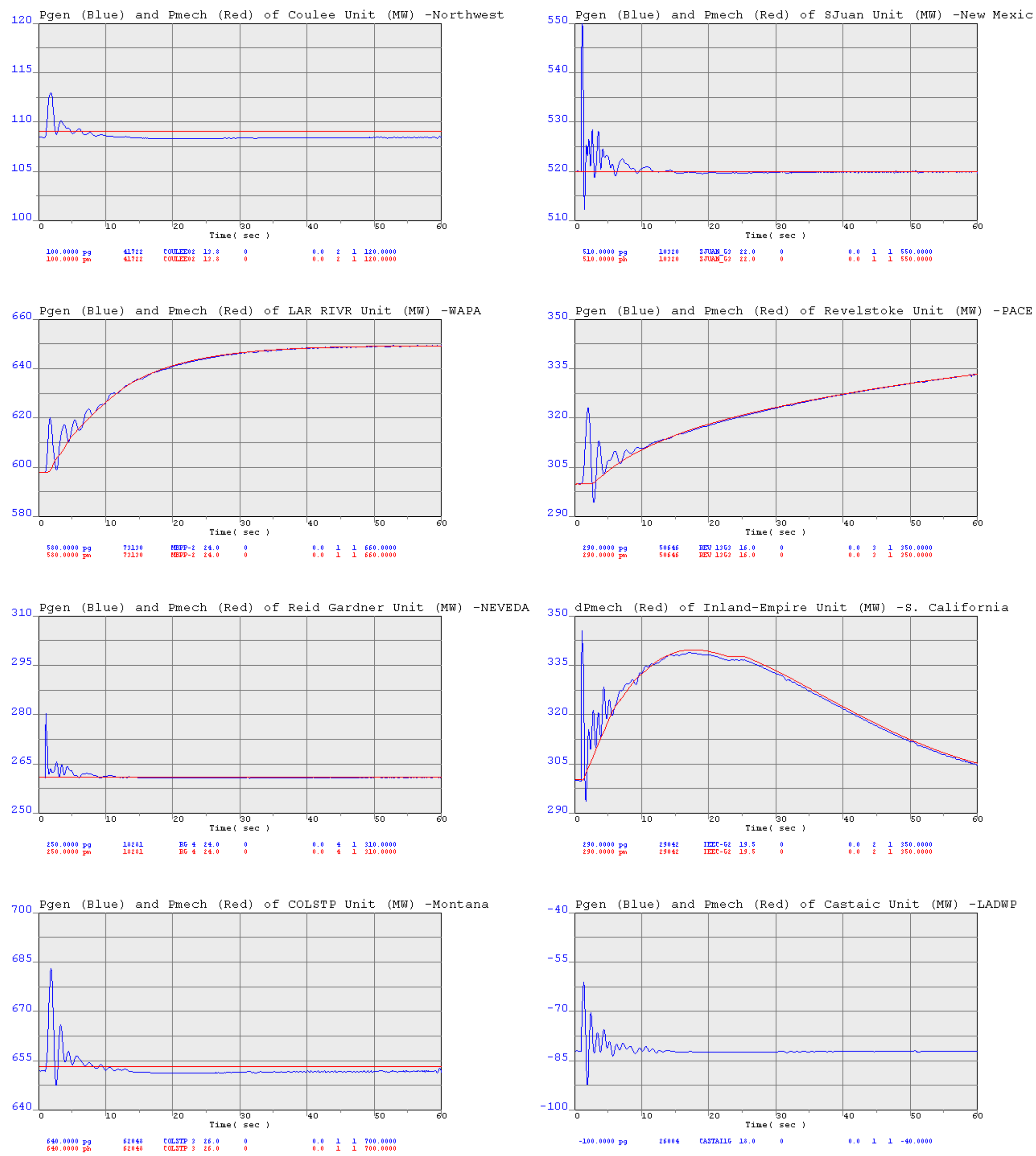

Figure A2 Governor Response to Loss of Two Palo Verde Units for Winter Low Load – High WECC Wind Case - Practical Minimum Spinning Reserves

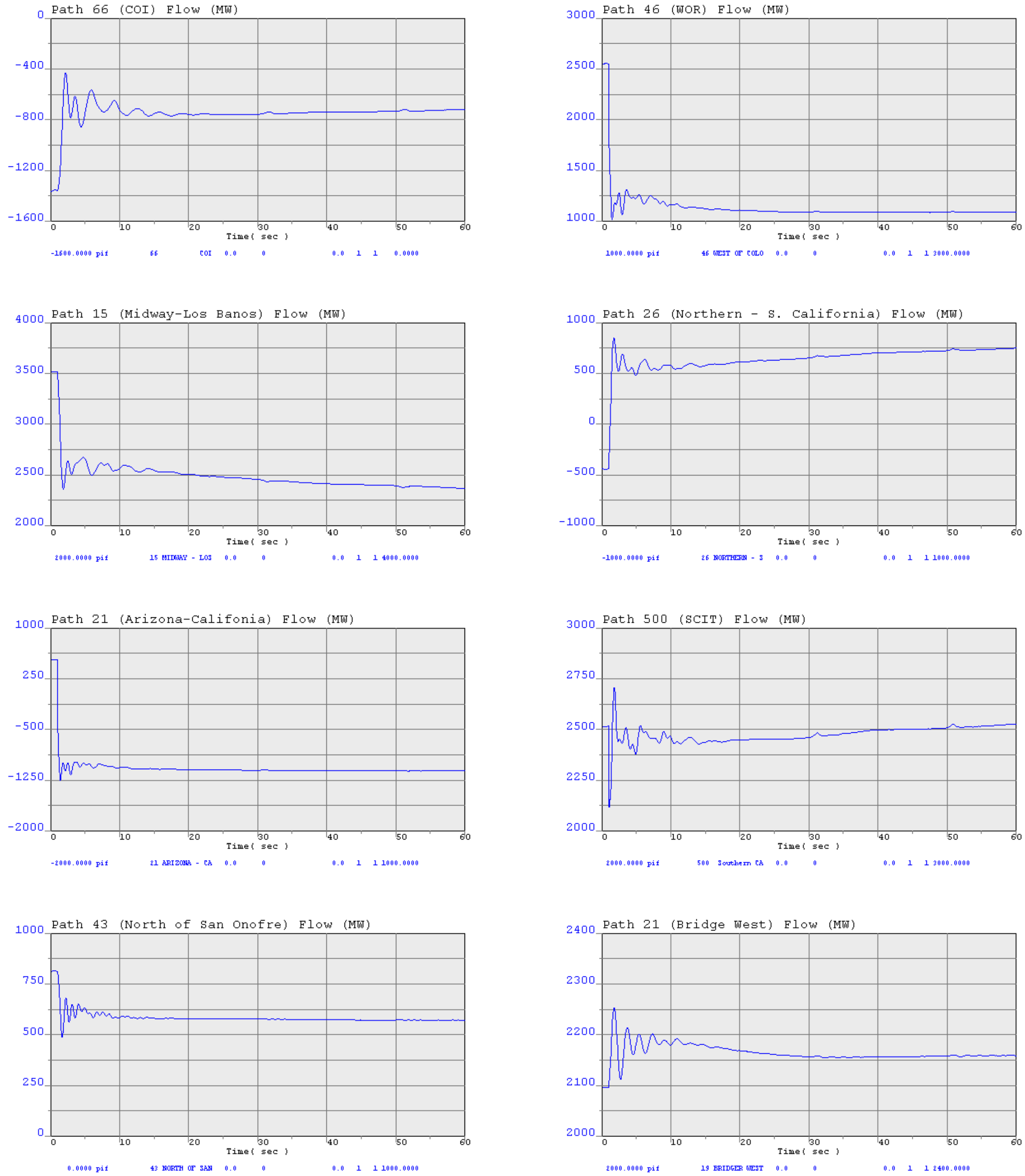

Figure A3 Interface Power Flow Response to Loss of Two Palo Verde Units for Winter Low Load – High WECC Wind Case - Practical Minimum Spinning Reserves

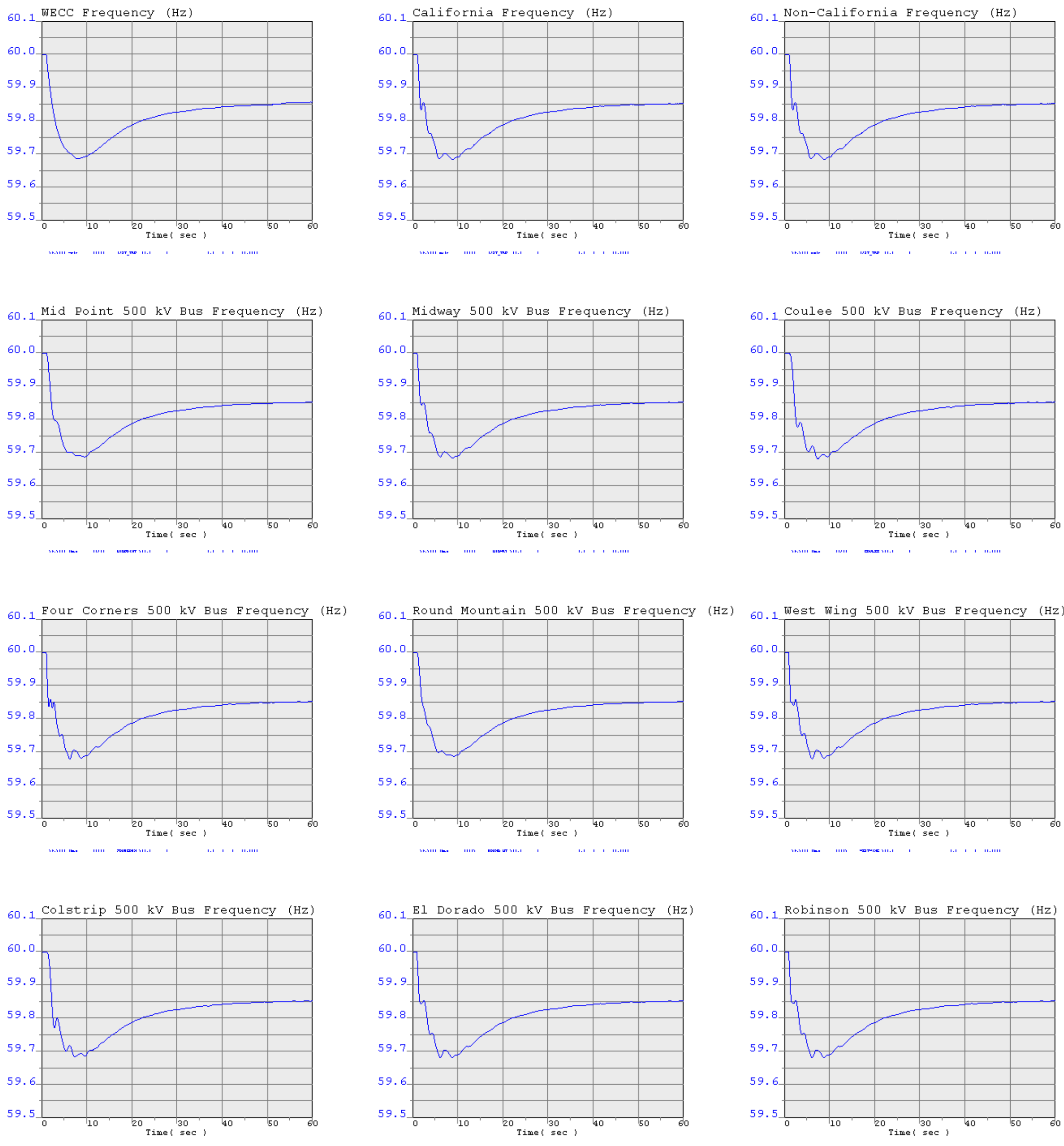

Figure A4 Frequency Behavior to Loss of Two Palo Verde Units for Weekend Morning – High CAISO Wind and Solar Base Case

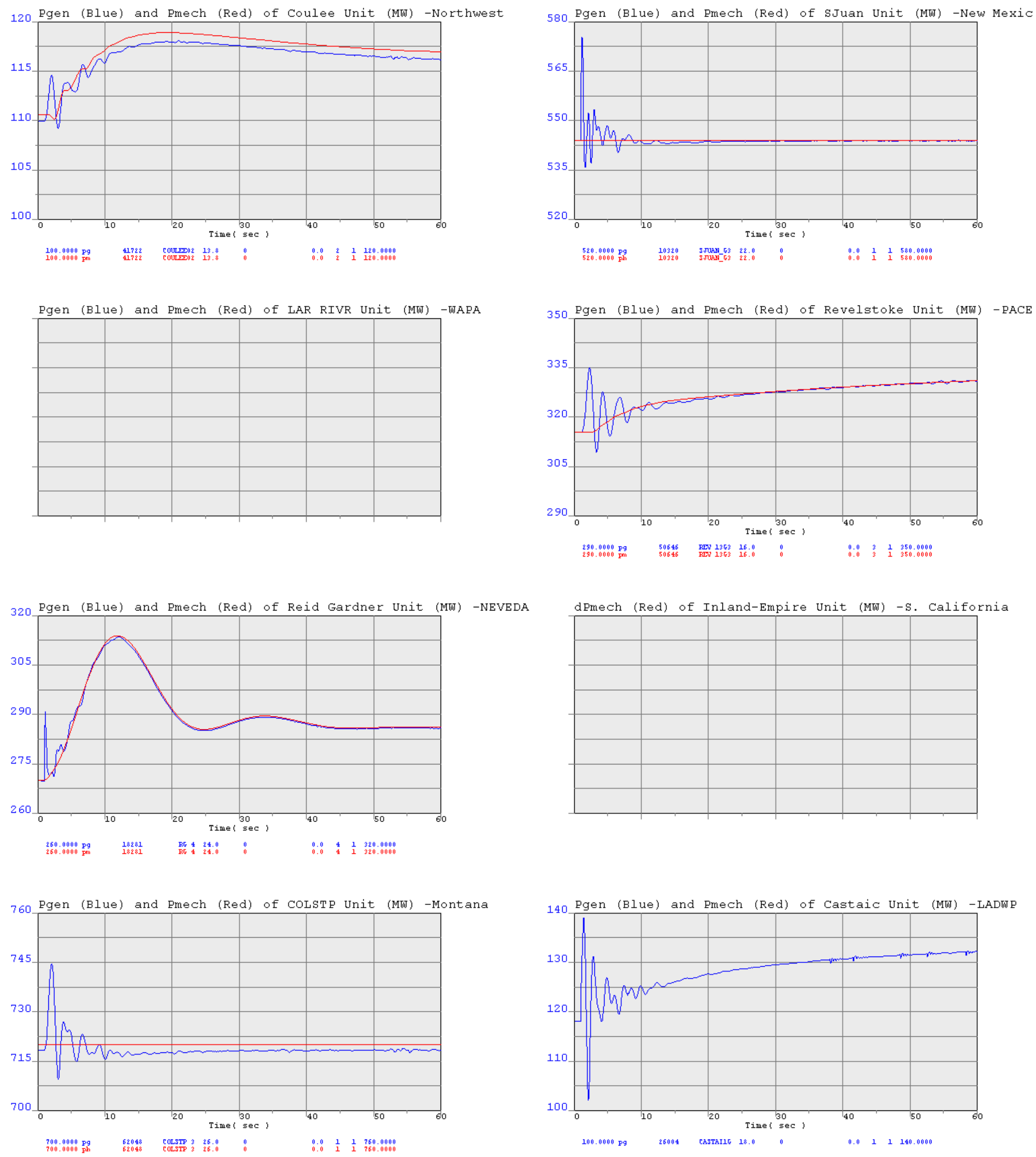

Figure A5 Governor Response to Loss of Two Palo Verde Units for Weekend Morning – High CAISO Wind and Solar Base Case

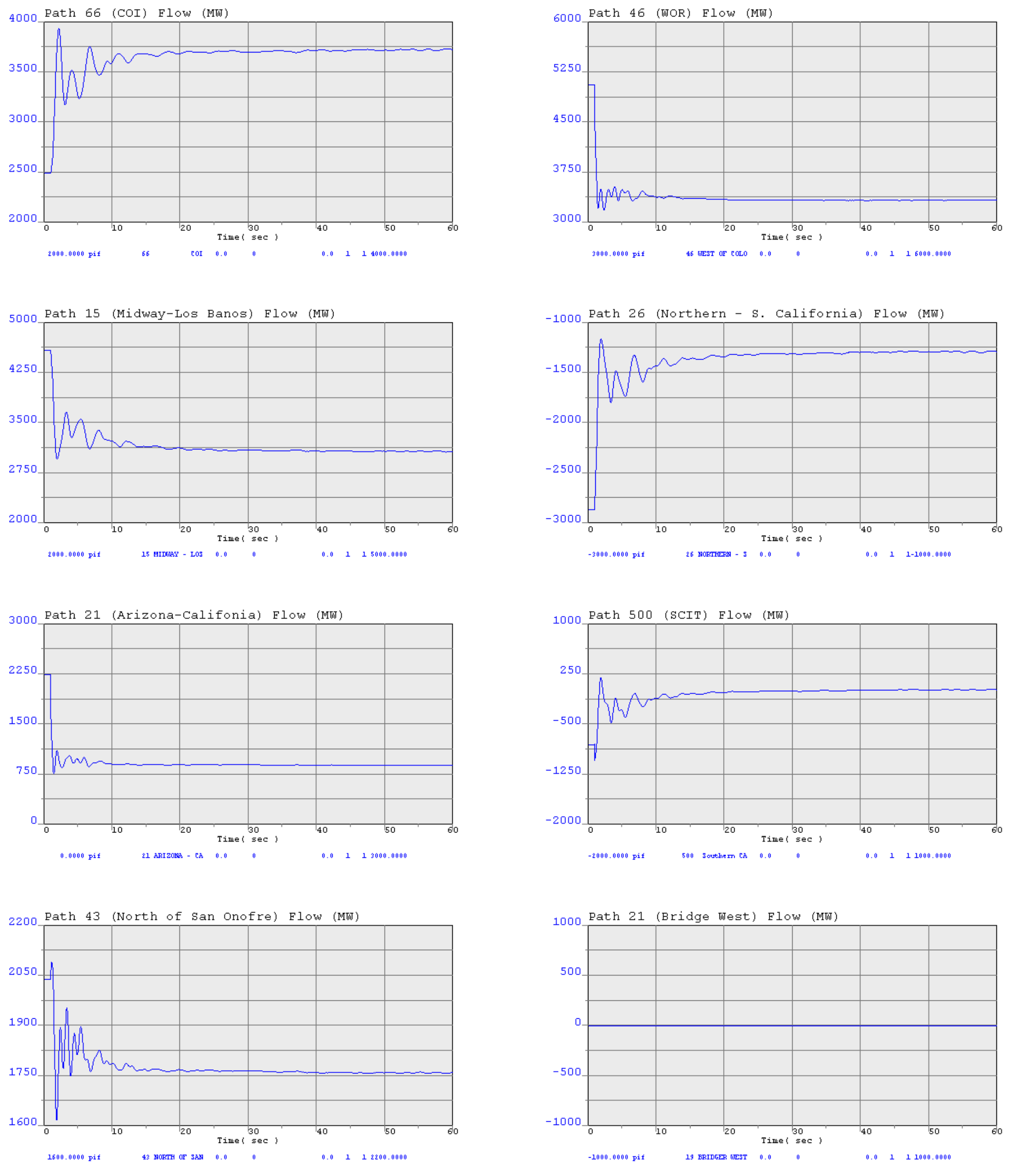

Figure A6 Interface Power Flow Response to Loss of Two Palo Verde Units for Weekend Morning – High CAISO Wind and Solar Base Case

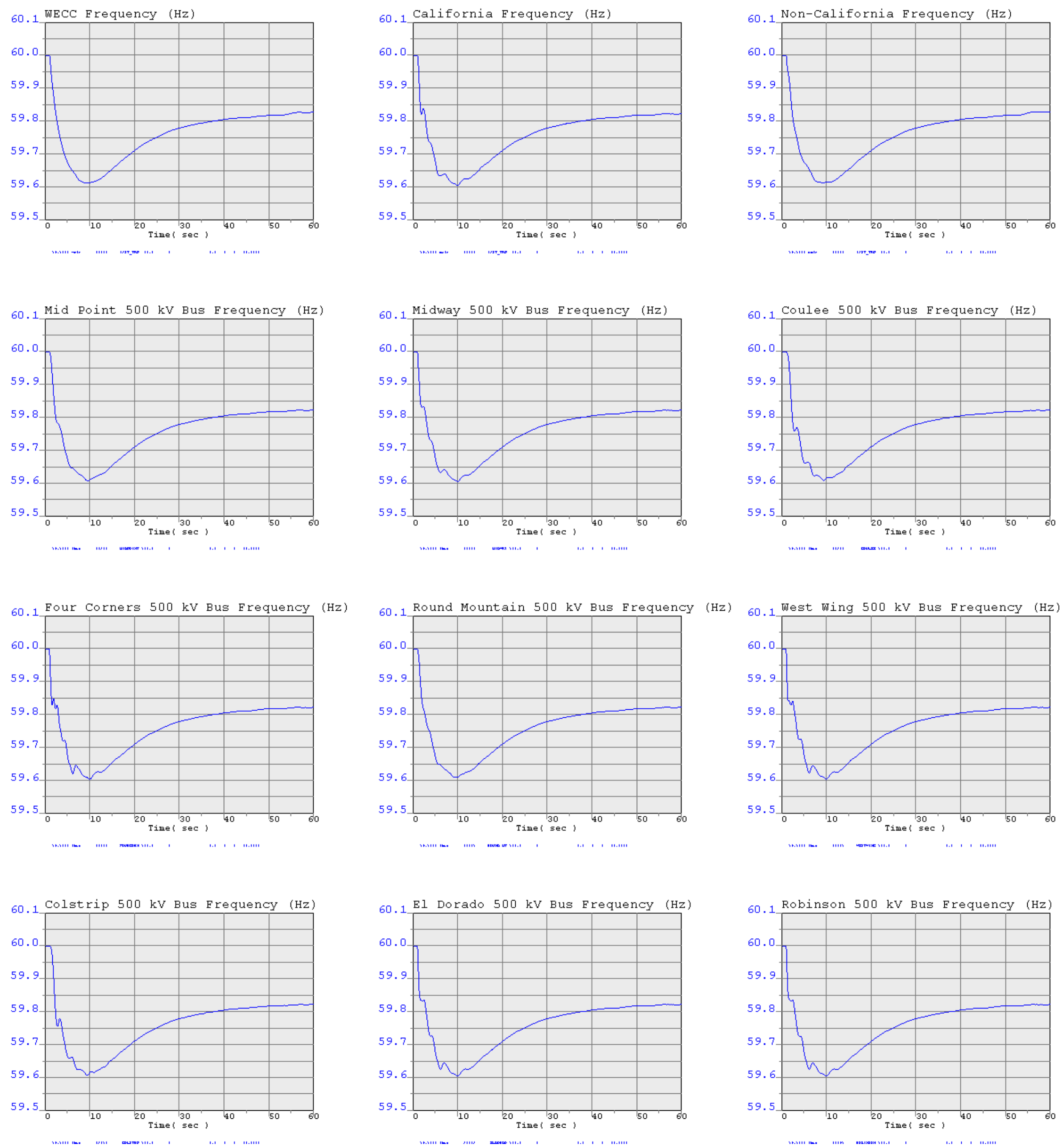

Figure A7 Frequency Behavior to Loss of Two Palo Verde Units for Weekend Morning – High WECC Wind and Solar Base Case

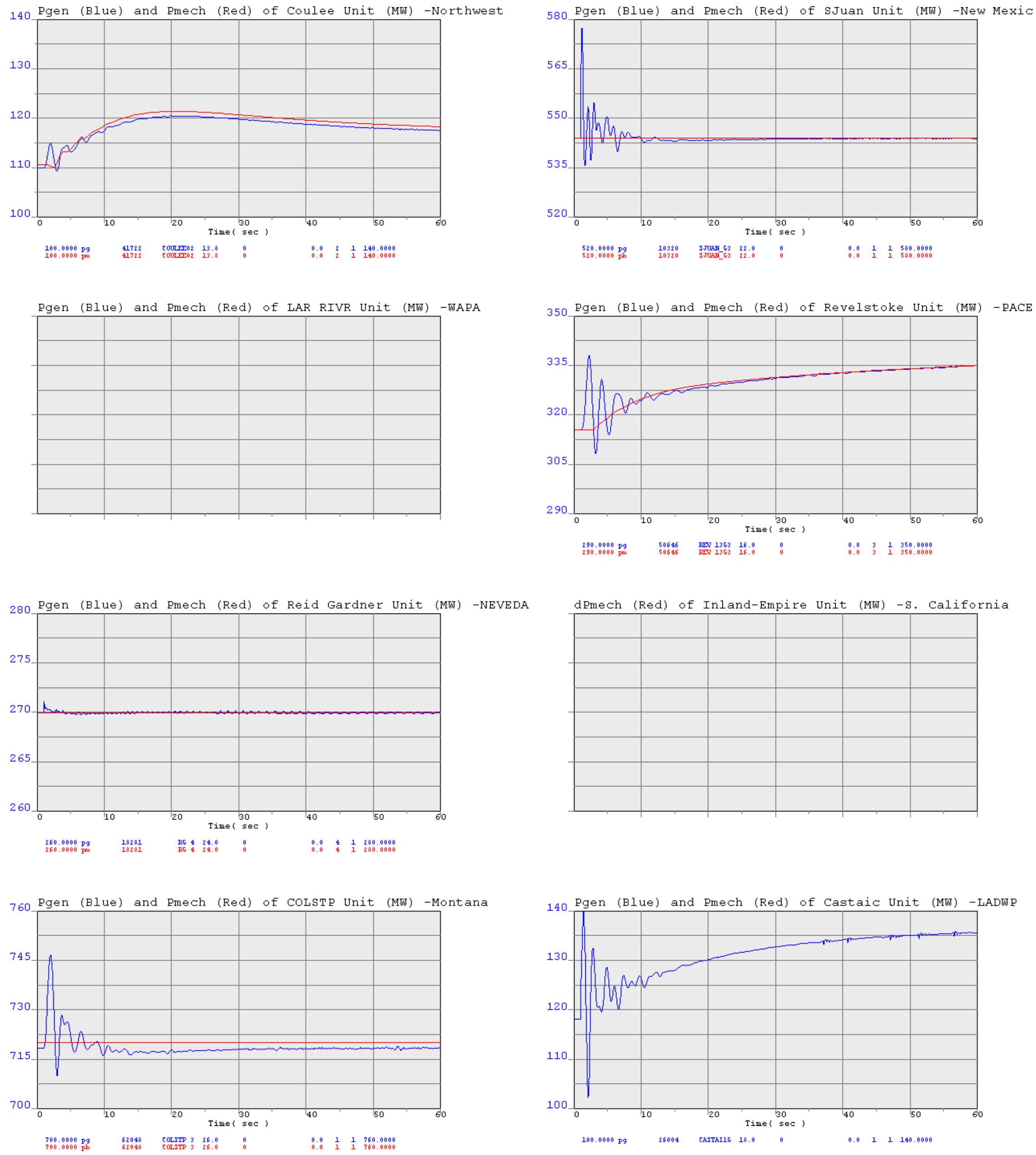

Figure A8 Governor Response to Loss of Two Palo Verde Units for Weekend Morning – High WECC Wind and Solar Base Case

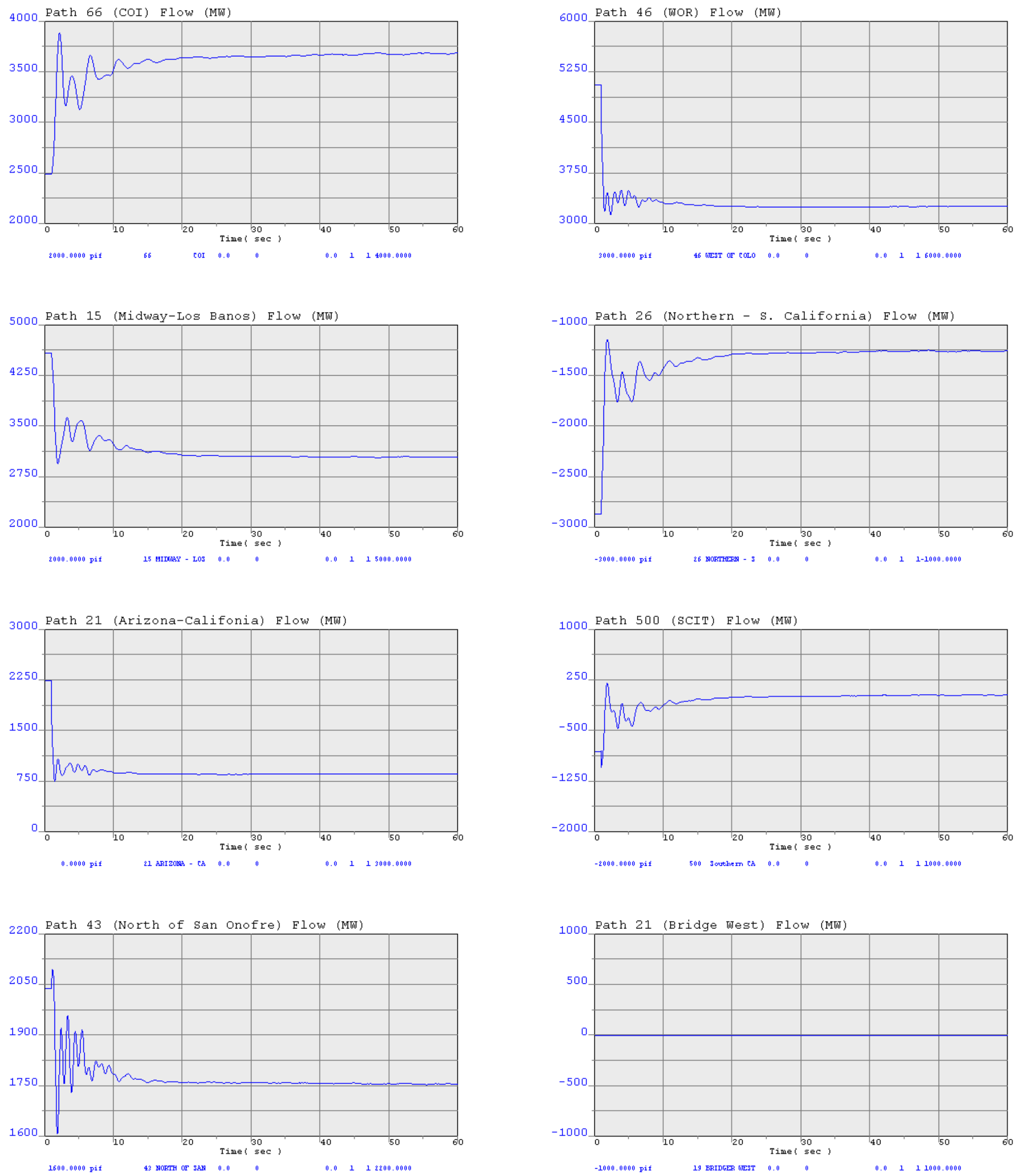

Figure A9 Interface Power Flow Response to Loss of Two Palo Verde Units for Weekend Morning – High WECC Wind and Solar Base Case

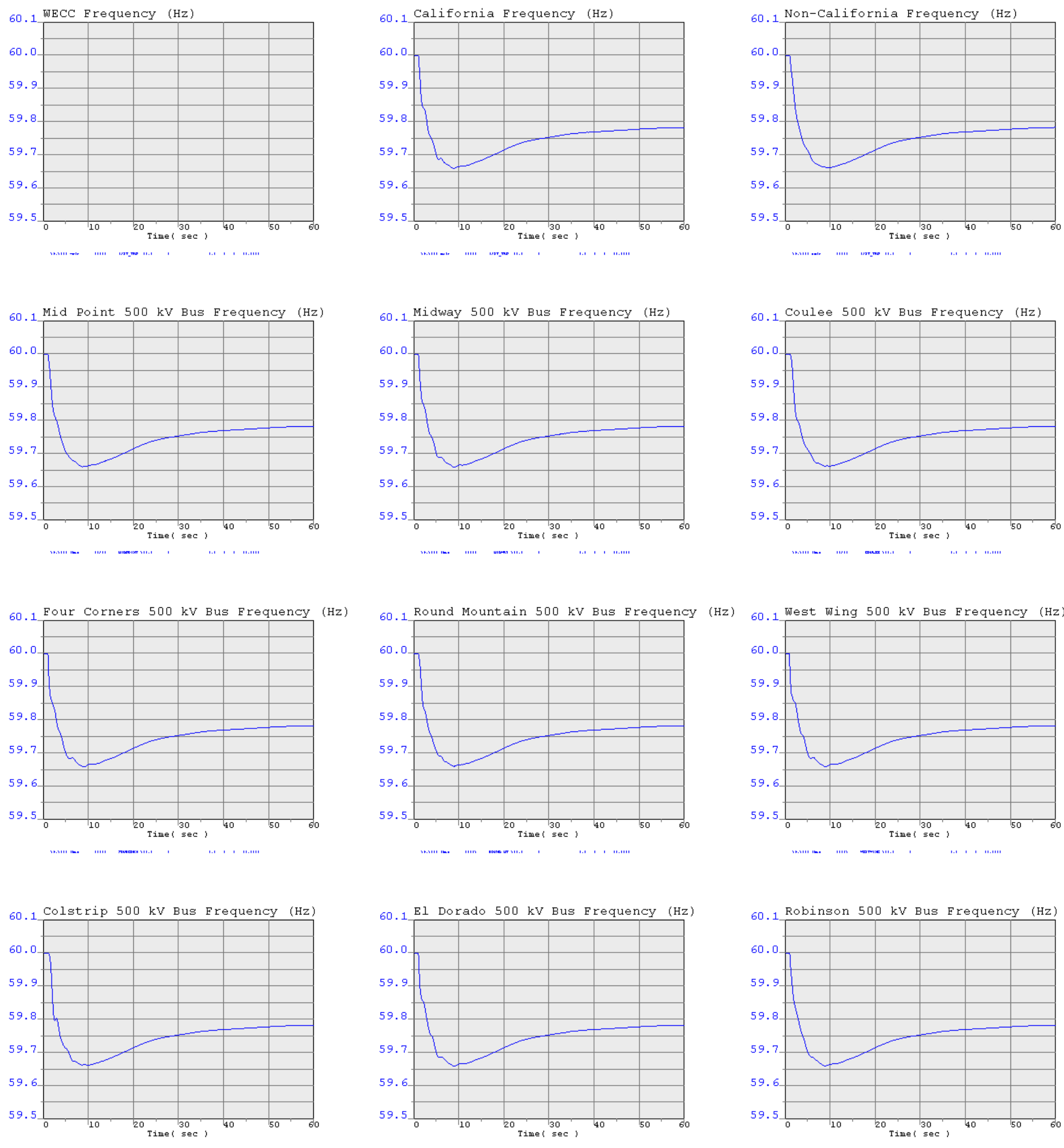

Figure A10 Frequency Behavior to Loss of Two Palo Verde Units for Winter Off Peak – High Wind Base Case

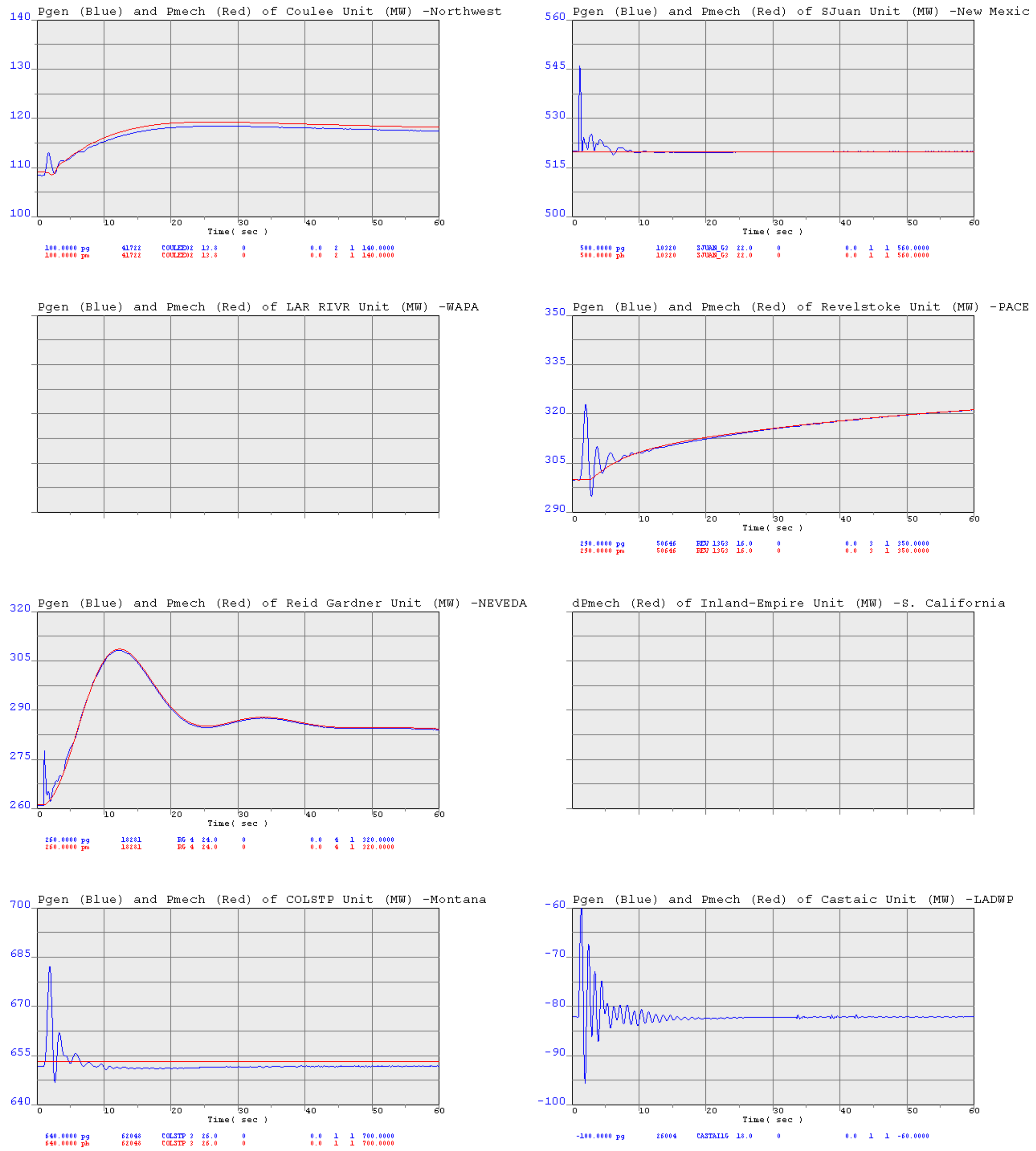

Figure A11 Governor Response to Loss of Two Palo Verde Units for Winter Off Peak – High Wind Base Case

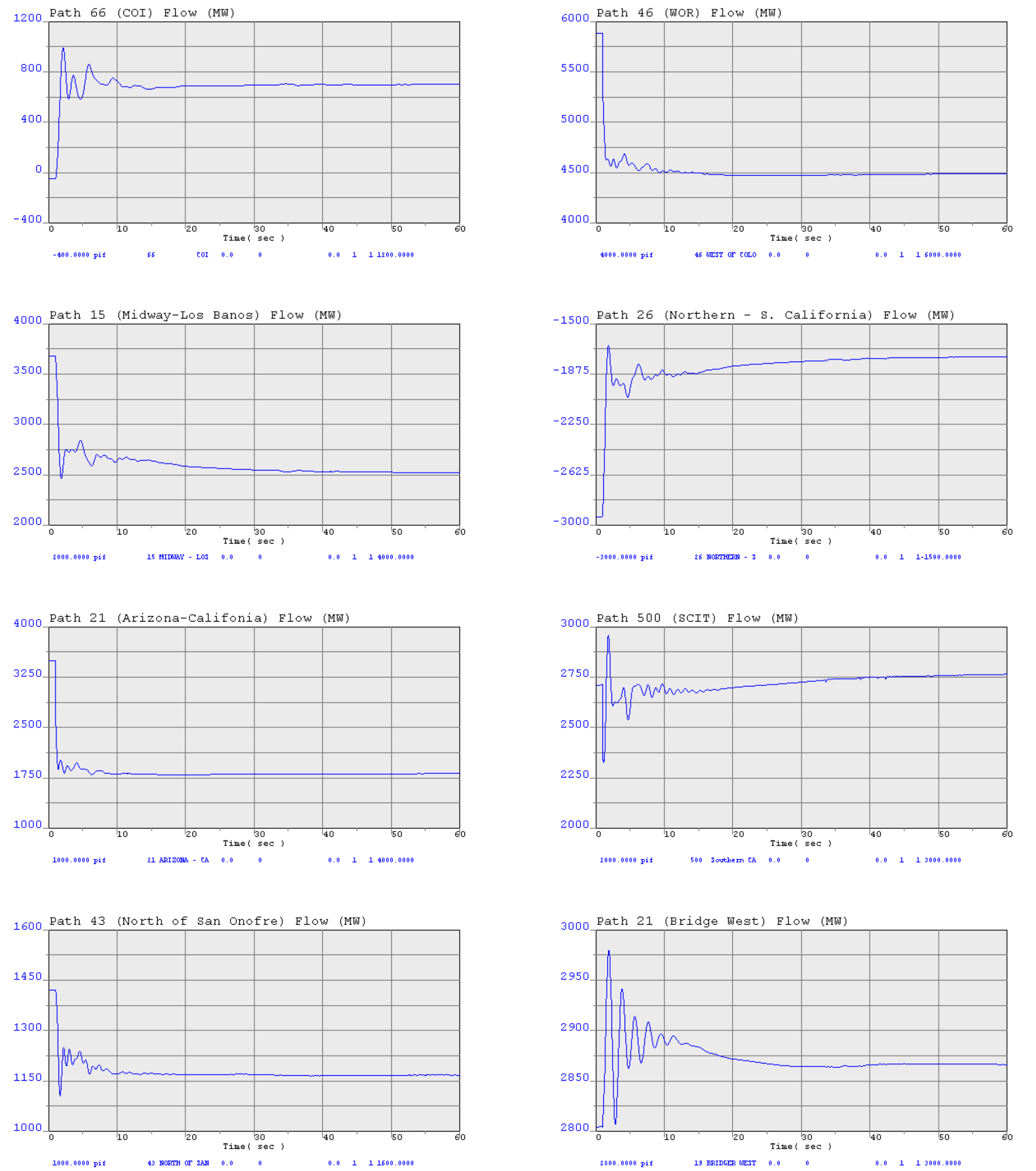

Figure A12 Interface Power Flow Response to Loss of Two Palo Verde Units for Winter Off Peak – High Wind Base Case

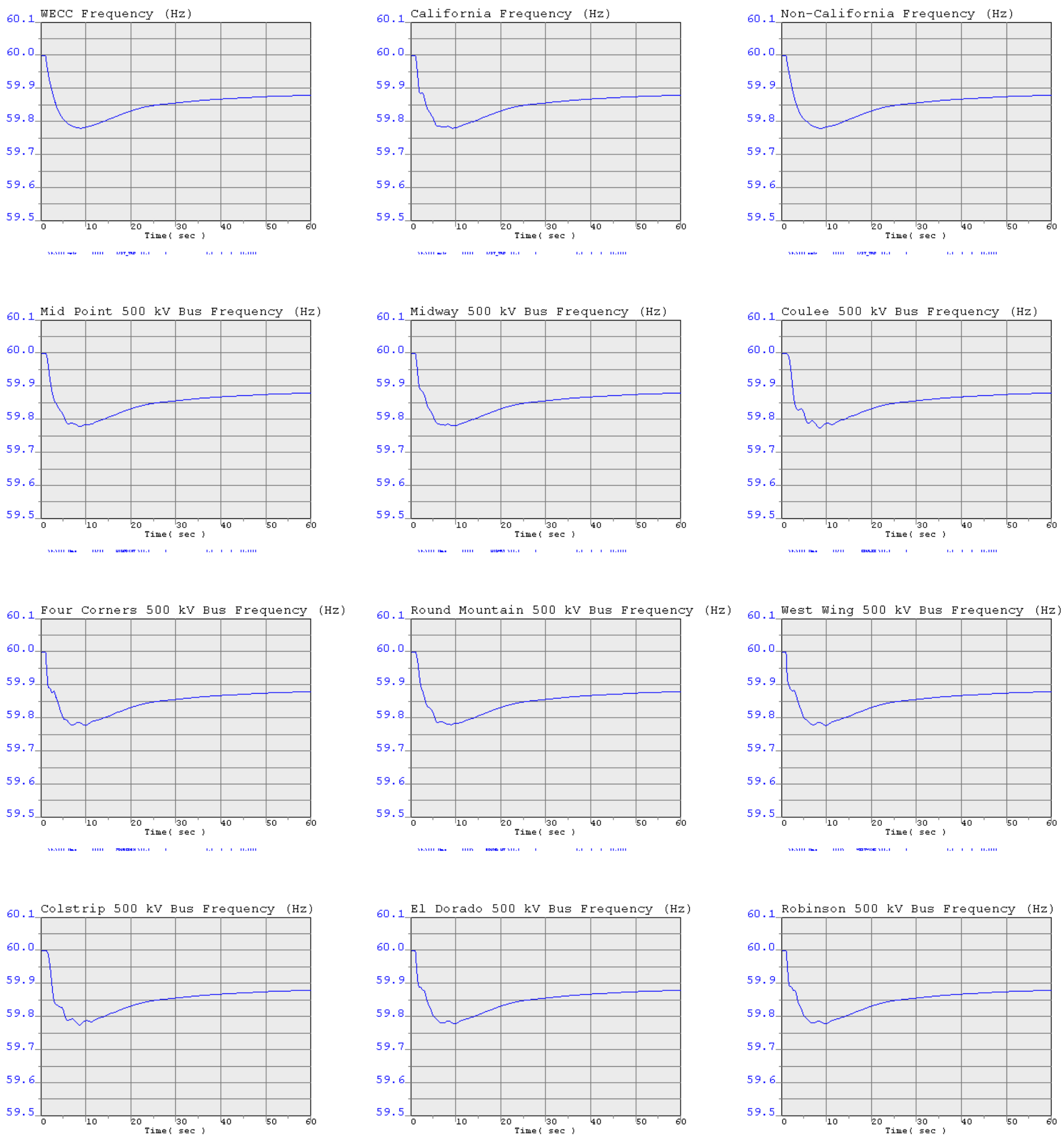

Figure A13 Frequency Behavior to Loss of Two Palo Verde Units for Spring Peak - High Hydro and Wind Base Case

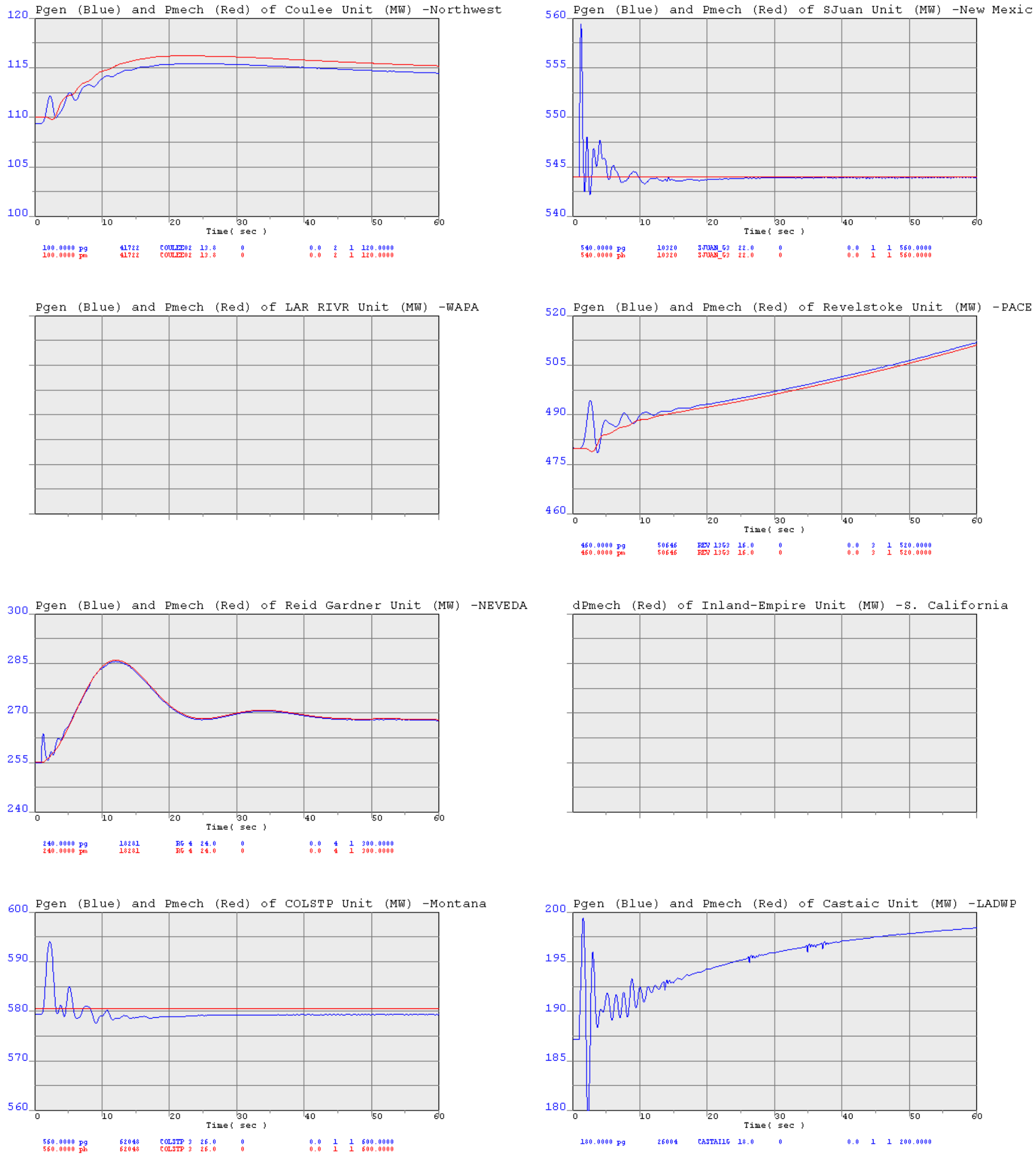

Figure A14 Governor Response to Loss of Two Palo Verde Units for Spring Peak - High Hydro and Wind Base Case

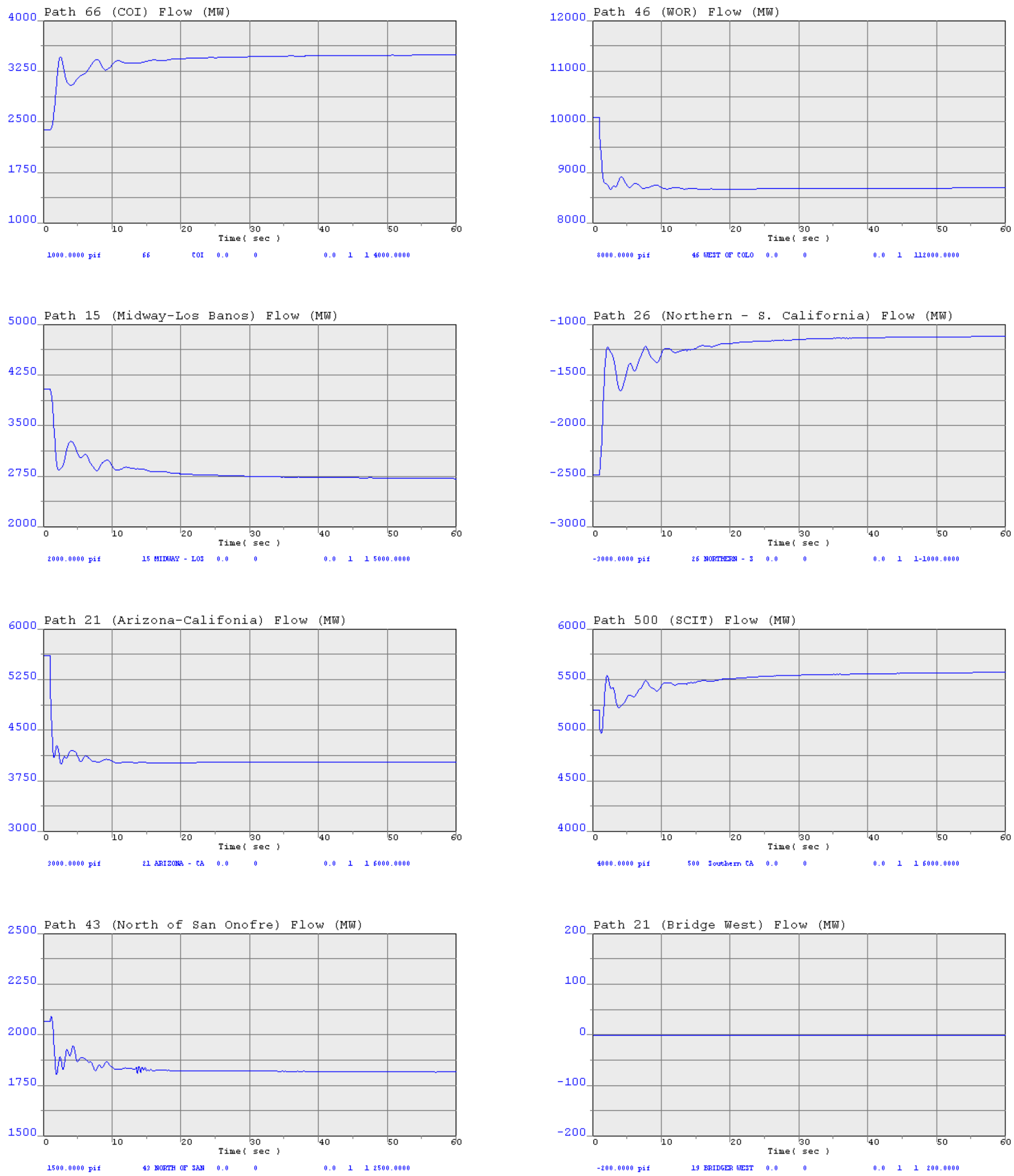

Figure A15 Interface Power Flow Response to Loss of Two Palo Verde Units for Spring Peak - High Hydro and Wind Base Case