CAISO Frequency Response Study

Stakeholder Conference

GE Energy

Nicholas W. Miller
Miaolei Shao
Sundar Venkataraman

CAISO

Mark Rothleder
Clyde Loutan
Irina Green

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imagination at work

California ISO
Shaping a Renewed Future

Outline

- Study Objectives
- Development of Study Database and Performance Metrics
- Frequency Response of Base Cases
- Frequency Response of High Renewable Penetration Cases
- Factors Affecting Frequency Response
- Mitigation Measures
- Conclusions

Frequency Response study

Concerns

- Frequency response would be lower due to lower inertia on the system
- Renewable resources replacing primary frequency control reserves
- Frequency decline following a large generator trip could trigger under-frequency load shedding relays
- Ability of the system to ride through faults without shedding load

Study Objectives

- Frequecny response to large generator outages under a variety of system conditions
    - Spring and winter load conditions
- The impact of unit commitment on frequency response
- The impact of generator output level on governor response
    - Headroom or unloaded synchronized capacity
    - Speed of governor response
    - Number of generators with governors
    - Governor withdrawal
- Potential mitigation measures

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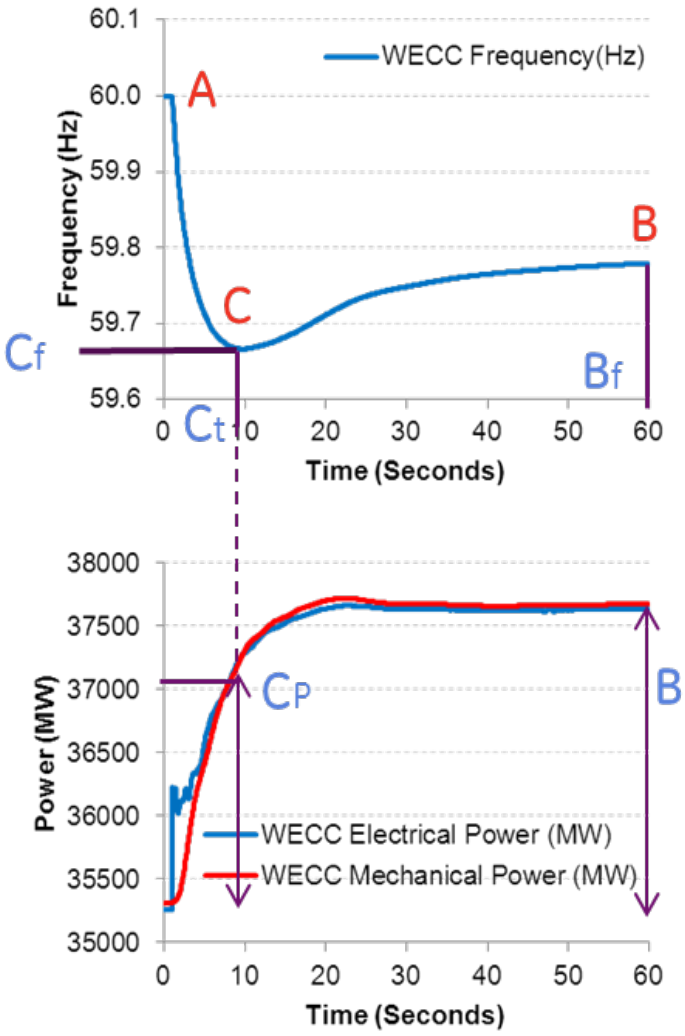
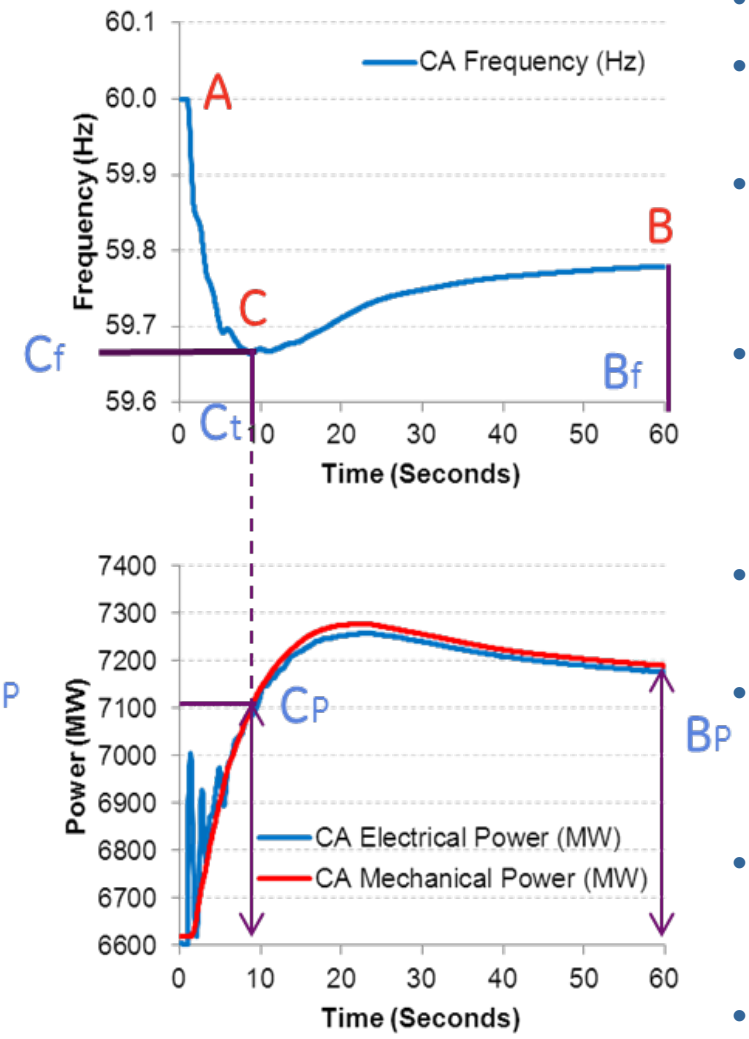
Study Base Case

This presentation focuses on the first two 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

Frequency Performance Metrics





- Frequency Nadir (Cf)
- Frequency Nadir Time (Ct)
- LBNL Nadir-Based Frequency Response (MW Loss/ Δf_c*0.1)
- GE-CAISO Nadir-Based Frequency Response (Δ MW/ Δf_c *0.1)
- Settling Frequency (Bf)
- NERC Frequency Response (MW Loss/ Δf_b*0.1)
- GE-CAISO Settling-Based Frequency Response
- (Δ MW/ Δf_b*0.1)

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)	The ratio between governor response (GR) and other conventional units
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

GR-Governor Response; BL-Base Load; NG-No Governor

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%	

Wind and Solar Power Summary for Winter Low Load – High CAISO Wind Base 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)

Penetration of wind and solar generation in California is 37%

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%	

Penetration of wind and solar generation in California is 50%

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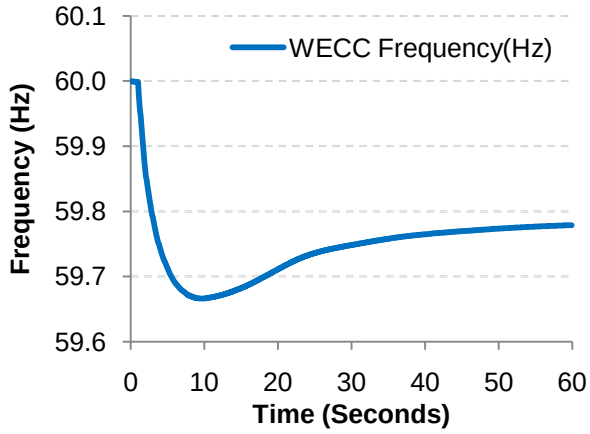
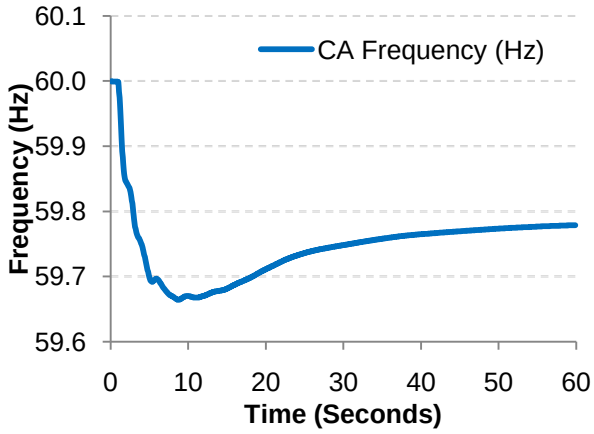
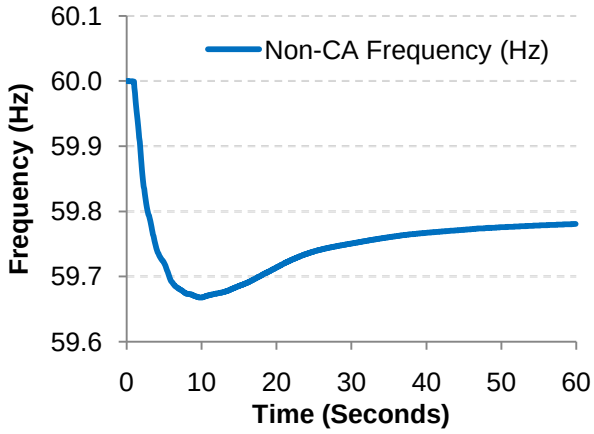
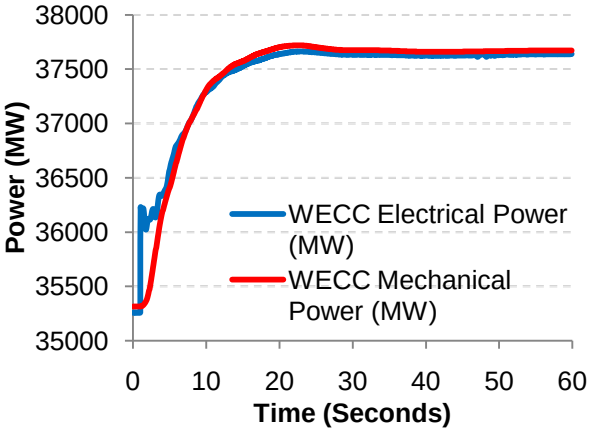
Frequency and Governor Response to Loss of Two Palo Verde Units

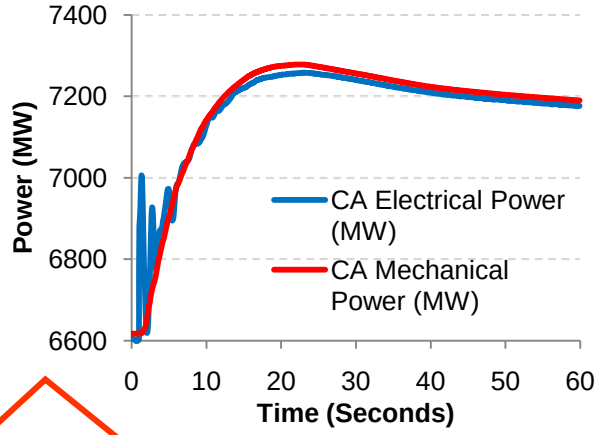
Winter Low Load – High CAISO Wind Base Case

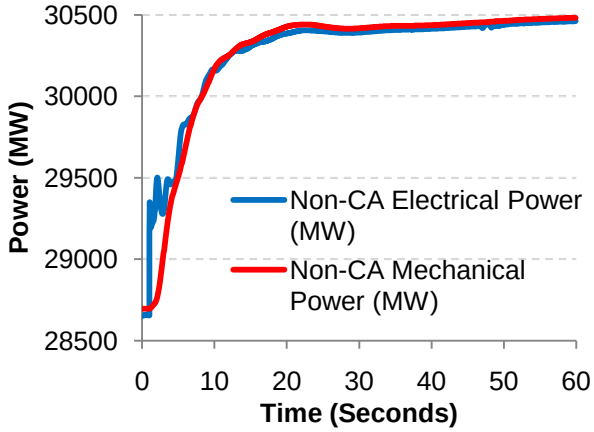












Governor responsive generation only

Performance Matrix for Loss of Two Palo Verde Units

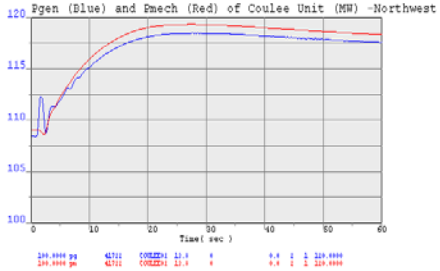
Winter Low Load – High CAISO Wind Base Case

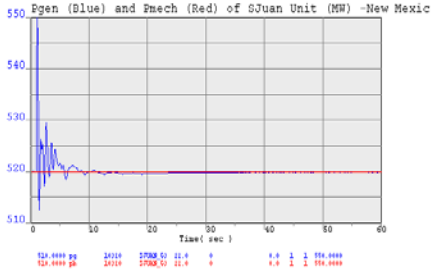
	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.67	59.66	59.67
Frequency Nadir Time (Seconds)	9.8	8.7	9.9
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	806	801	810
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	641	154	479
Percent of Total (%)		24.0	74.7
Settling Frequency (Hz)	59.78	59.78	59.78
NERC Frequency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

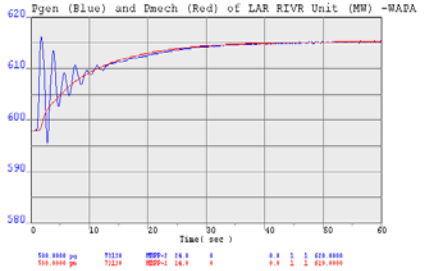
Governor Response and Grid Flow

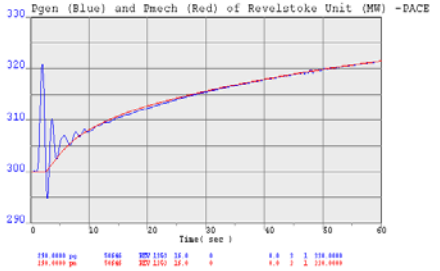
electric and mechanical power of selected machines

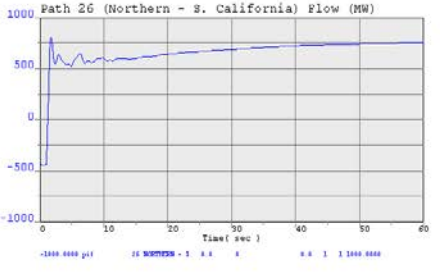
Power flow of selected key interfaces

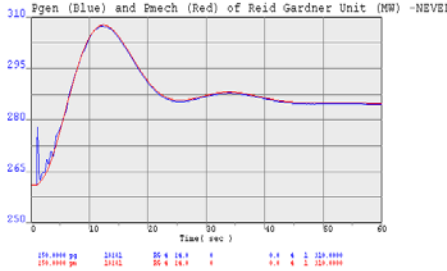


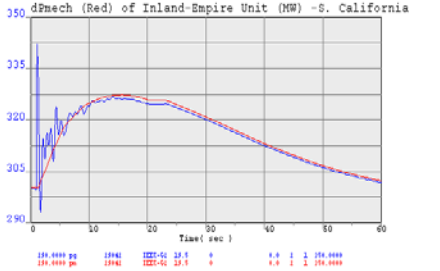


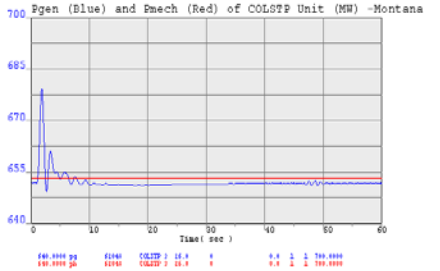


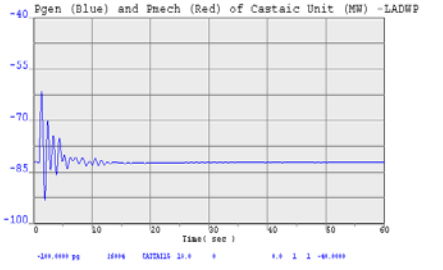






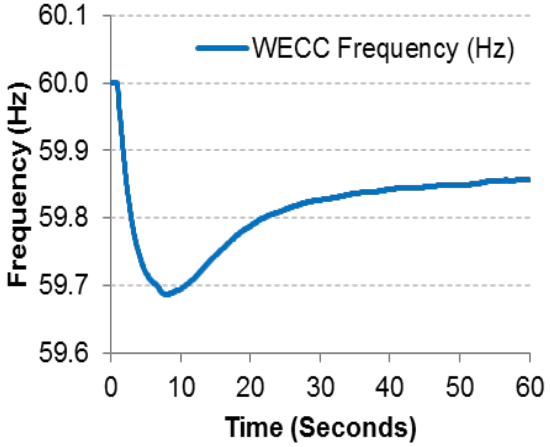


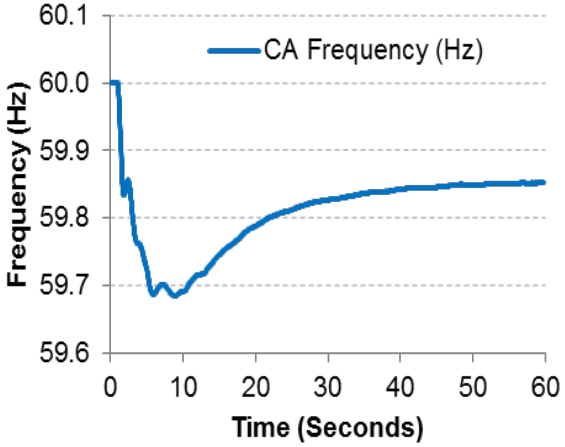


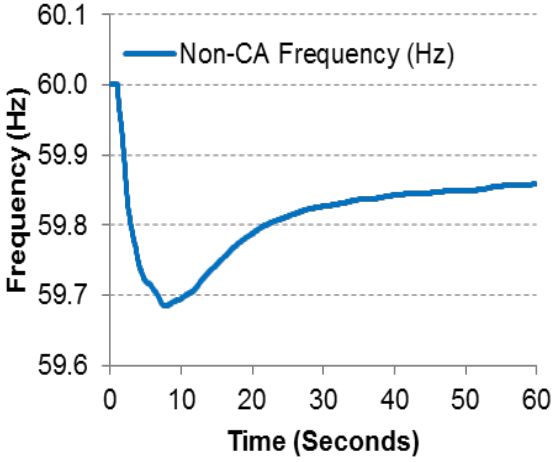


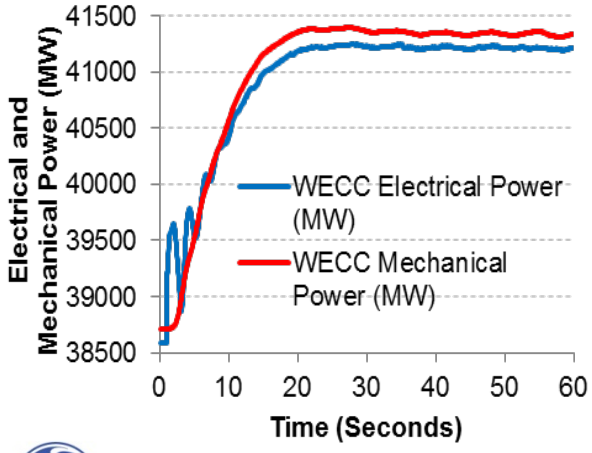
Frequency and Governor Response to Loss of Two Palo Verde Units

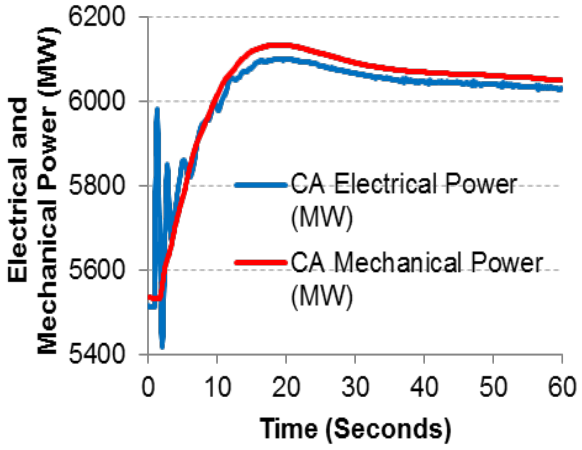
Weekend Morning – High CAISO Wind and Solar Case

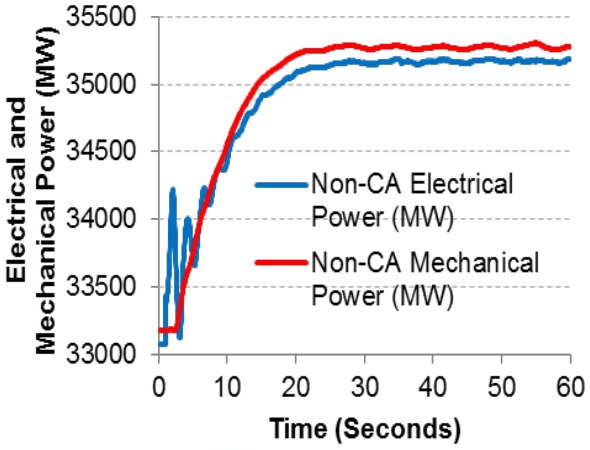












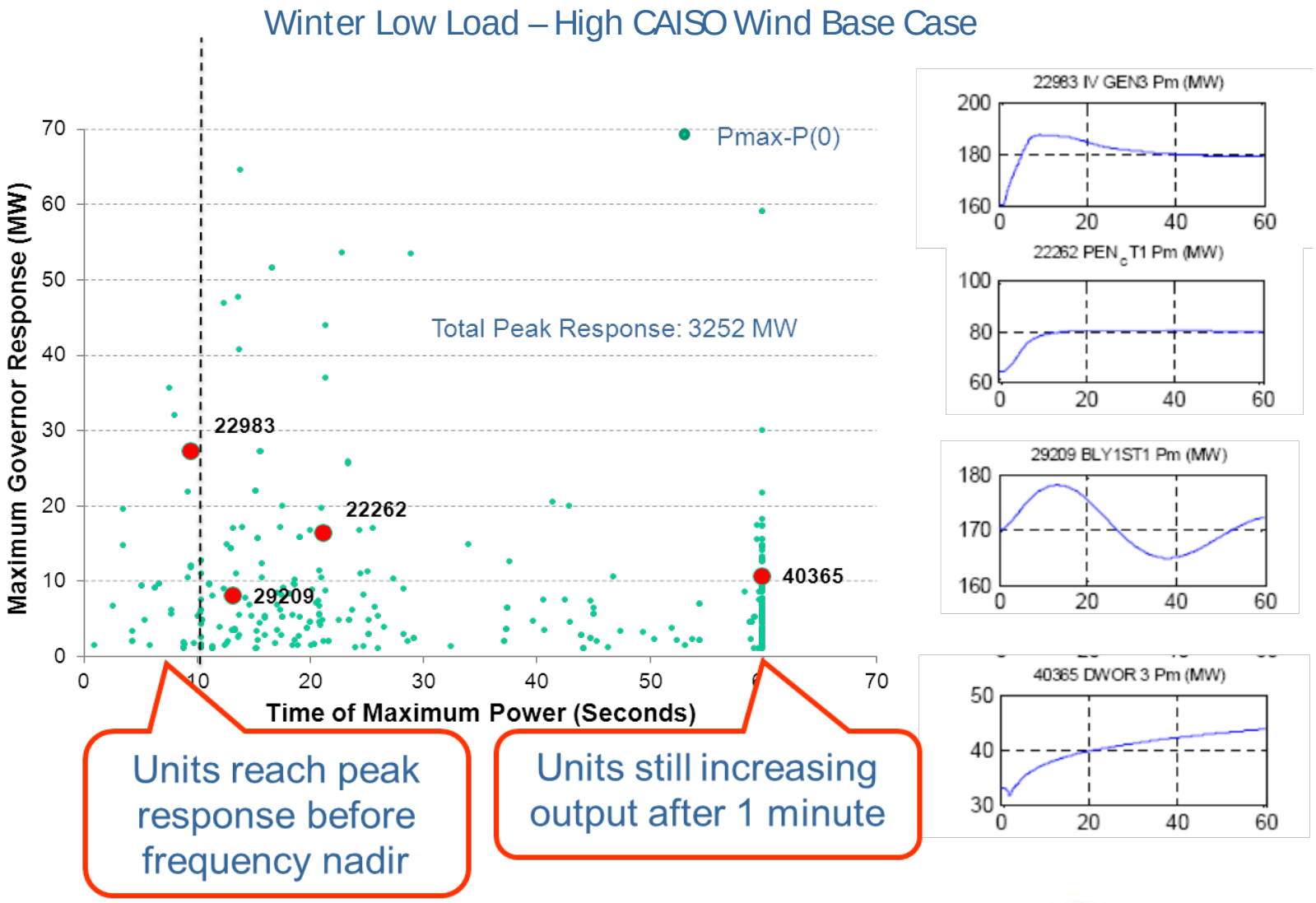
Performance Matrix for Loss of Two Palo Verde Units

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

287 MW/0.1Hz is comfortably above the proposed target of 205 MW/0.1Hz

Governor Response Discussion - Timing of Governor Response

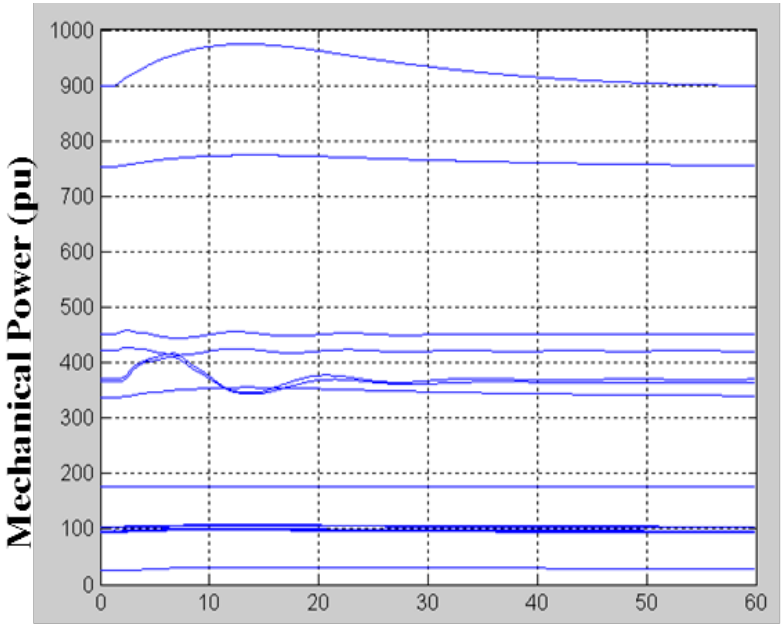


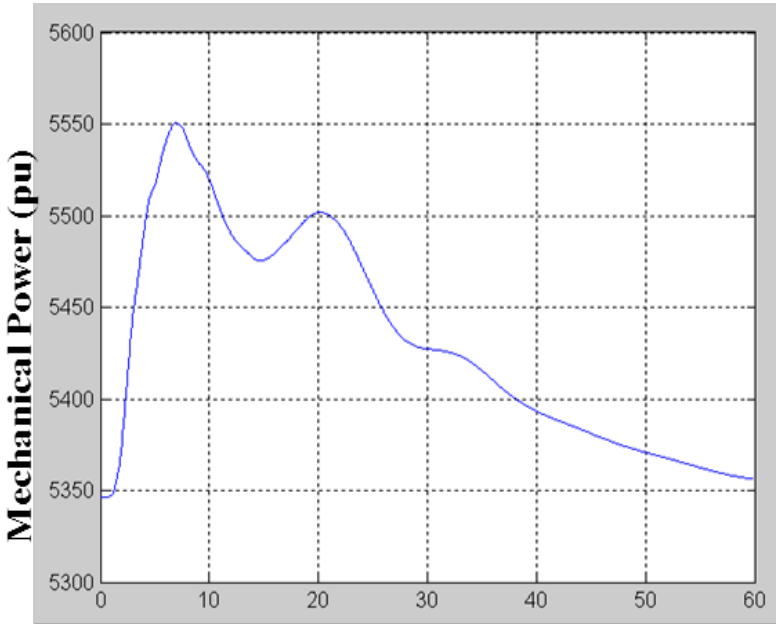
Governor Response Discussion - Governor Withdrawal with Load Control Response

Winter Low Load – High CAISO Wind Base Case

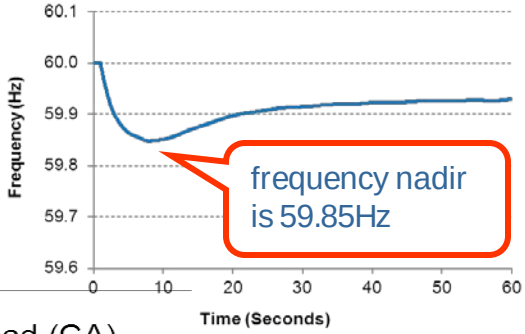
18 governor resposne units, with total generation of 5338 MW, have turbine load controller model (lcfb1) model

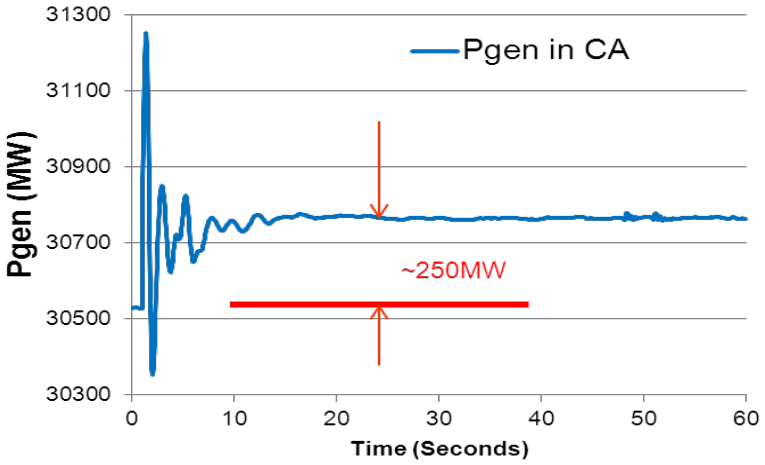
200 MW of governor response is deliberately withdrawn, representing almost 10 percent of total frequency response

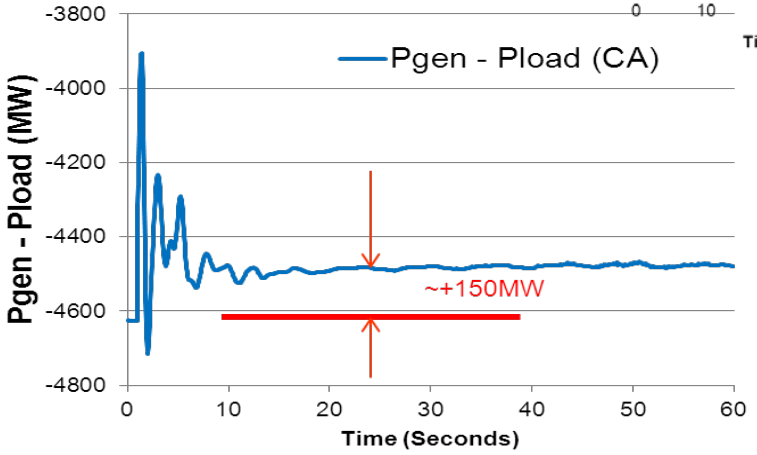


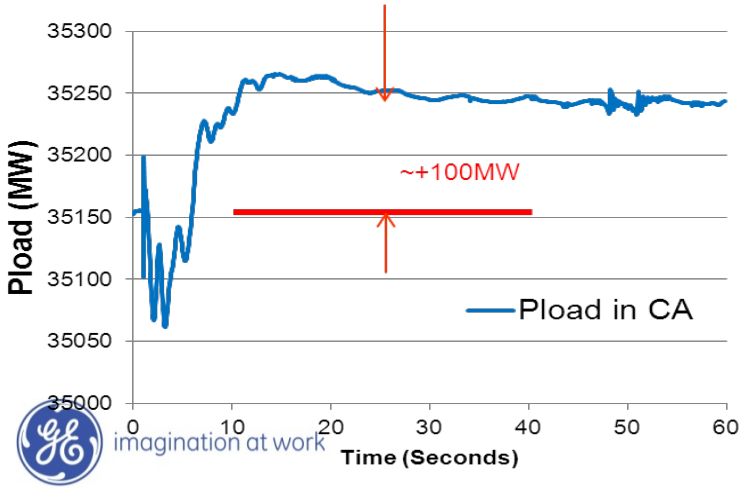


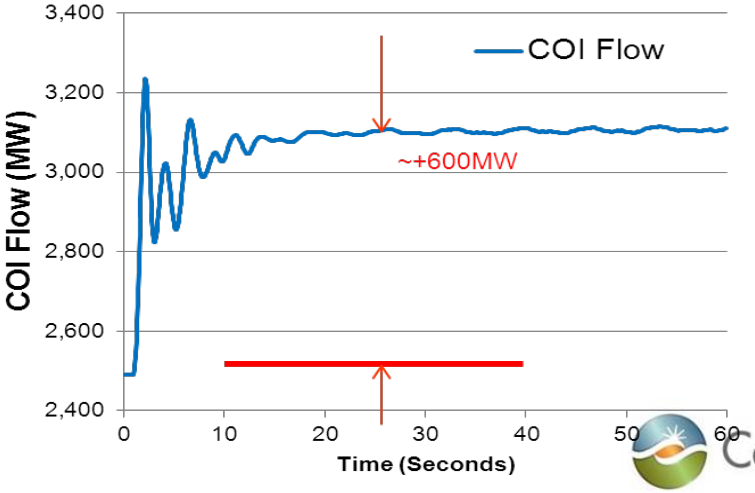
Single Palo Verde Unit Trip Event (1345 MW) - Response of California Generation, Load and COI Flow











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Generation Summary for Winter Low Load – High CAISO Wind Base Case

See this slide before

	WECC		CA		Non-CA	
		# of Units		# of Units		# of Units
GR Pgen (MW)	35353	513	6602	122	28652	391
GR MWCAP (MW)	48993		10576		38417	
GR Headroom (MW)	13640		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	
GR MWCAP + BL Pgen + NG Pgen + Wind Pgen	105268		32827		72	
CU Pgen (MW) (GR + BL + NG)	78287	1164	20442	359	57	
Total Pgen (MW)	94392		29683		64	
Total Pload (MW)	91300		26190		651	
Wind Pgen/Total Pgen	14.1%		28.3%		7.6%	
Solar Pgen/Total Pgen	2.7%		8.6%		0.0%	
GR MWCAP/(GR MWCAP + BL Pgen + NG Pgen + Wind Pgen) - Kt	46.5%		32.2%		53.0%	
GR Pgen/CU Pgen	45.2%	44.1%	32.3%	34.0%	49.6%	48.6%
GR Pgen/Total Pgen	37.5%		22.2%		44.3%	
GR Headroom/CU Pgen	17.4%		19.4%		16.9%	
GR Headroom/Total Pgen	14.5%		13.4%		15.1%	

Wind generation in outside of California is relatively low.

Re-dispatch Methodology

WWSIS study's 2/3-1/3 "rule" - 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.

The selection of conventional thermal units to be replaced by WTG is based on MAPS results in the WWSIS study - the least annual operating time.

50 conventional thermal units, with total power generation of 4754 MW and total MVA rating of 7888 MVA, were selected to be replaced by WTGs. 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, were selected to modify MVA rating and MWCAP.

The replacement and re-dispatch results in a net decrease of 3169 MVA of committed units and a net increase of 1585 MW unloaded generation. Note that the increase in headroom is 1211 MW, since some units downwardly dispatched machines do not have governors.

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%	

Increased from 7.6% to 15% .

Comparison of Wind and Solar Power Summary

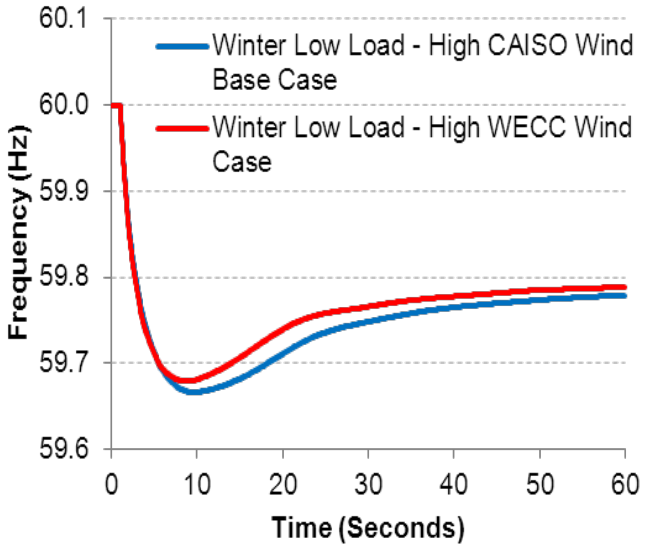
Winter Low Load – High CAISO Wind Base Case

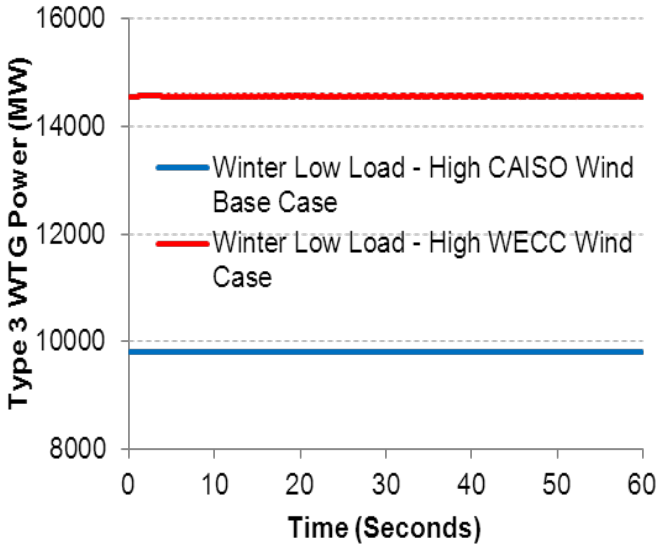
	WECC		CA		Non-CA	
TOTAL Pgen	94392		29683		64710	
TOTAL Pload	91300		26190		65111	
WIND&SOLAR (MW)						
	WECC		CA		Non-CA	
TP 1	2494(wind)	398(solar)	2160(wind)	398(solar)	334(wind)	0(solar)
TP 2	444(wind)		444(wind)		0(wind)	
TP 3	9809(wind)		5213(wind)		4597(wind)	
TP 4	594(wind)	1738(solar)	594(wind)	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)

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)

Comparison of Impact 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

More wind has better frequency response.

The rate-of-change-of-frequency (ROCOF) is nearly same.

Renewable penetration alone gives little insight.

Headroom and Kt are better metrics of anticipated performance.

Generation Summary for Weekend Morning – High WECC Wind and Solar 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%	

Comparison of Wind and Solar Power Summary

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)

Weekend Morning – High WECC Wind and Solar 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)

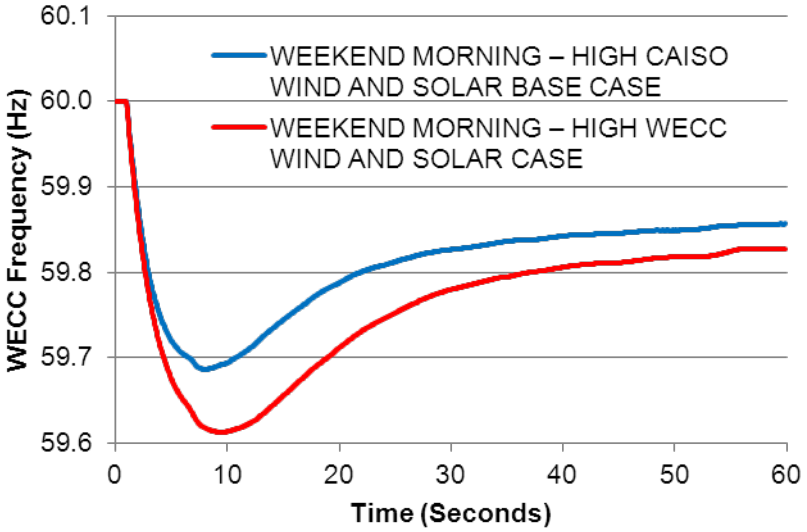
Comparison of Impact of Increasing Levels of Wind on Frequency Performance to Loss of Two Palo Verde Units

More wind has worse but acceptable frequency response.

California's frequency response improves (from 287 to 311 MW/0.1 Hz – well above the 205 MW/0.1Hz target).

The fractional contribution in California increases greatly, from 20% to 27%.

The behavior of resources outside of California has impact on the California response.



	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

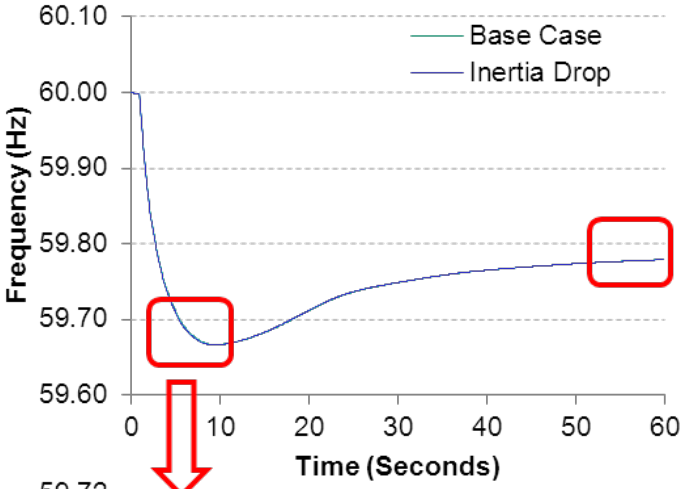
Outline

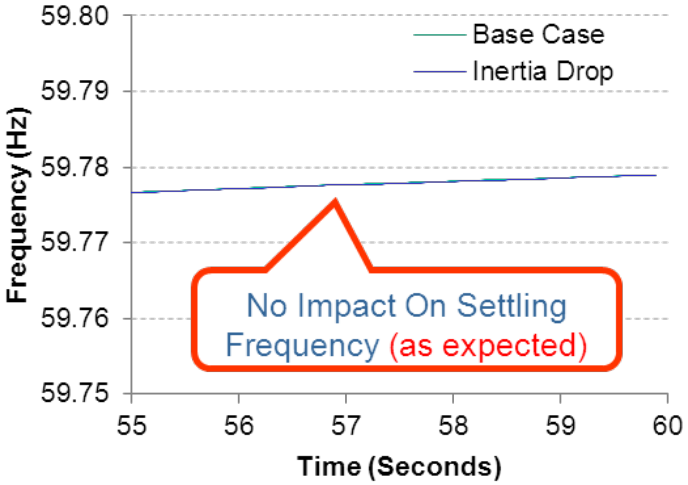
- Study Objectives
- Development of Study Database and Performance Metrics
- Frequency Response of Base Cases
- Frequency Response of High Renewable
- Factors Affecting Frequency Response
- Mitigation Measures
- Conclusions

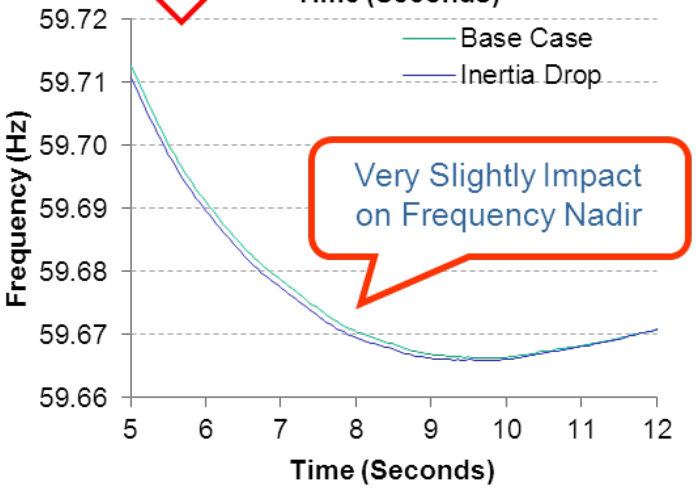
Factors Affecting Frequency Response

	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

Factors Degrading Frequency Response – Reduced Inertia







The impact of loss of inertia for 1993 MW is nearly invisible.

Keep all other factors impacting frequency response fixed

- same Kt and headroom
- Wind and Solar are held constant

Baseload units that contribute inertia

- 14 base load units, with total MVA rating of 1993 MVA and dispatch of 324 MW, were de-committed.
- 2 other base load units, with total MVA rating of 1762 MVA and dispatch of 591 MW, were selected to dispatched up 324 MW.

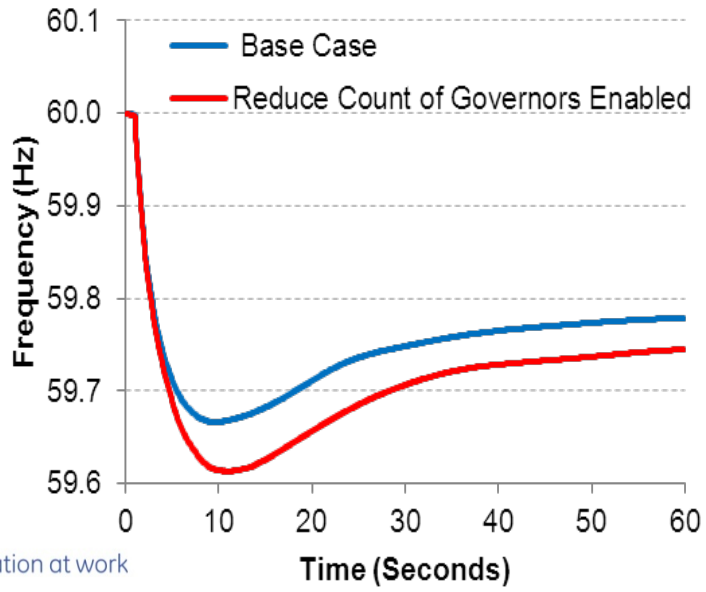
Factors Degrading Frequency Response – Fewer Governors in Operation

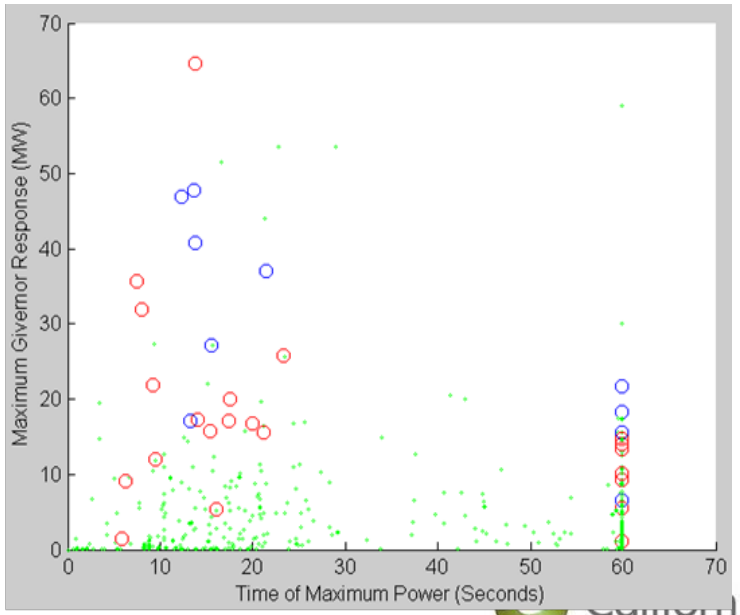
Keep all other factors impacting frequency response fixed

Governor Response (GR) units

- 25 GR units, with total dispatch 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 base load.
- Another 11 GR units, with total dispatch of 3034MW and rating (MWCAP) of 4165 MW were selected to dispatch down 2045 MW.

Reduce the count of generators providing response by 25, while holding headroom fixed.





Factors Degrading Frequency Response – Reduced Headroom

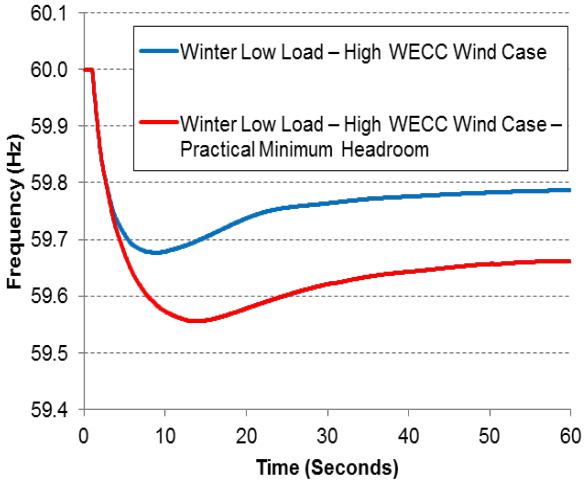
- Small Change in Headroom
- Practical Minimum Headroom
- Extreme minimum Headroom

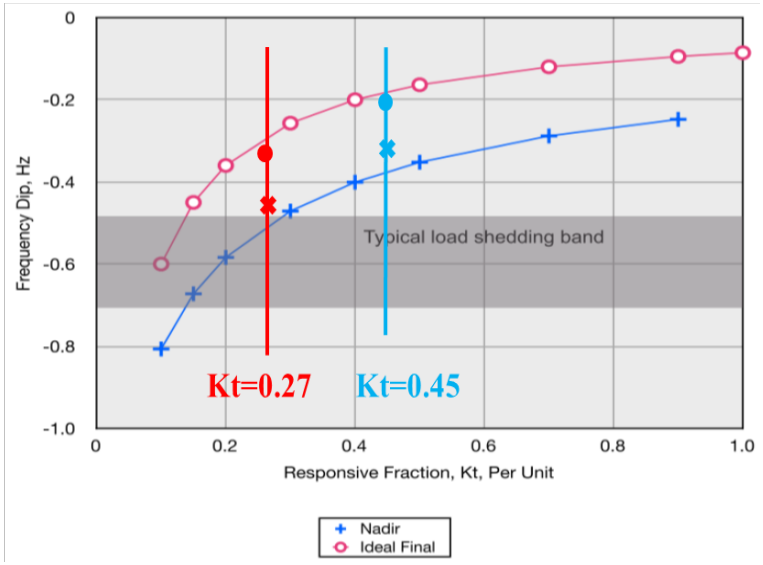
Reduce Headroom - Practical Minimum Headroom

	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) 13640	8115	3974	3124	9765	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%	

Condition in this case was considered to be challenging and might occur relatively infrequently.

Reduce Headroom - Practical Minimum Headroom





	Winter Low Load – High WECC Wind Case			Winter Low Load – High WECC Wind Case – Practical Minimum Spinning Reserves		
	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

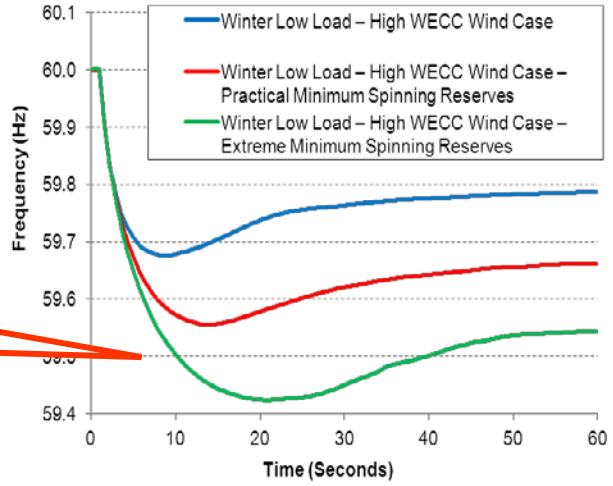
Generation Summary for Winter Low Load – High WECC Wind Case – Extreme Minimum Headroom

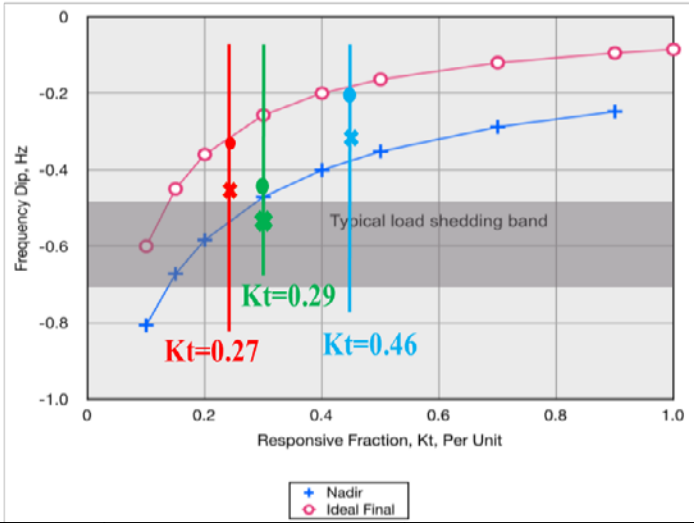
	WECC		CA		Non-CA	
		# of Units		# of Units		# of Units
GR Pgen (MW)	23913	284	7018	92	16895	192
GR MWCAP (MW)	27057		8169		18888	
GR Headroom (MW) 13640	3144		3974 1151		9765 1993	
BL Pgen (MW)	39676	510	11439	168	28238	342
NG Pgen (MW)	9678	320	2617	99	7060	221
Wind Pgen (MW)	18094		8411		9684	
Solar 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%	

Impact of Extreme Minimum Headroom and Governor Participation (Kt) on Frequency Performance

Winter Low Load – High WECC Wind Case

UFLS relay off





Kt alone is insufficient to anticipate frequency performance.

Headroom should be considered – at least when it is in short supply.

Time or time window for which settling frequency is measured becomes quite important.

	Winter Low Load – High WECC Wind Case			Winter Low Load – High WECC Wind Case – Practical Minimum Spinning Reserves			Winter Low Load – High WECC Wind Case – Extreme Minimum Spinning Reserves		
	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

Outline

- Study Objectives
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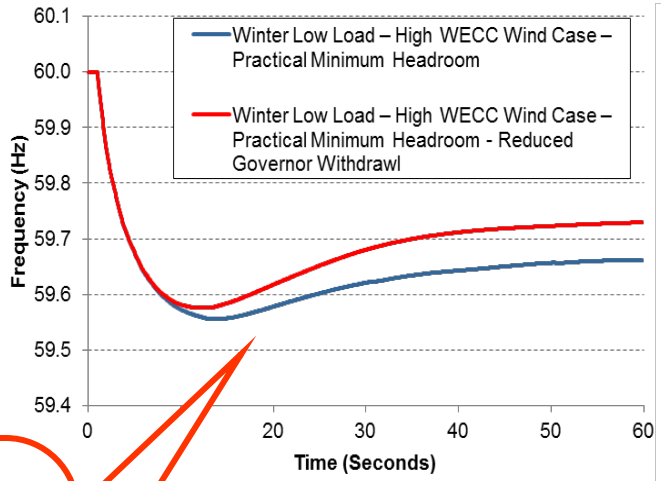
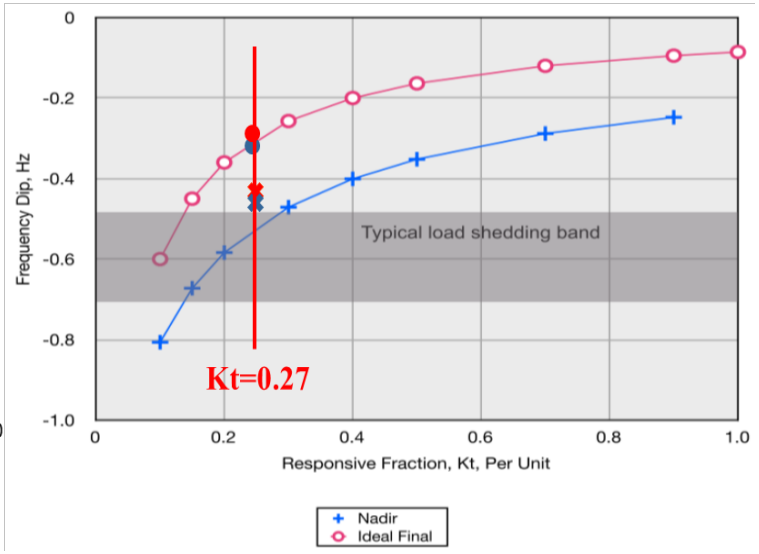
- Frequency Response of Base Cases
- Frequency Response of High Renewable Penetration Cases
- Factors Affecting Frequency Response
- Mitigation Measures
  - Reduced Governor Withdrawal
  - Inertial Response From Wind Plants
  - Governor Response (Frequency Droop) from Wind Plants
  - Load Control/Fast Energy Storage
- Conclusions

Mitigation Measures – Reduced Governor Withdrawal

Disable load control on the 18 units with lcfb1 model.





Load control has relatively small impact on the frequency nadir.

Settling frequency is significantly impacted.

Withdrawal causes a 20% degradation in NERC frequency response.

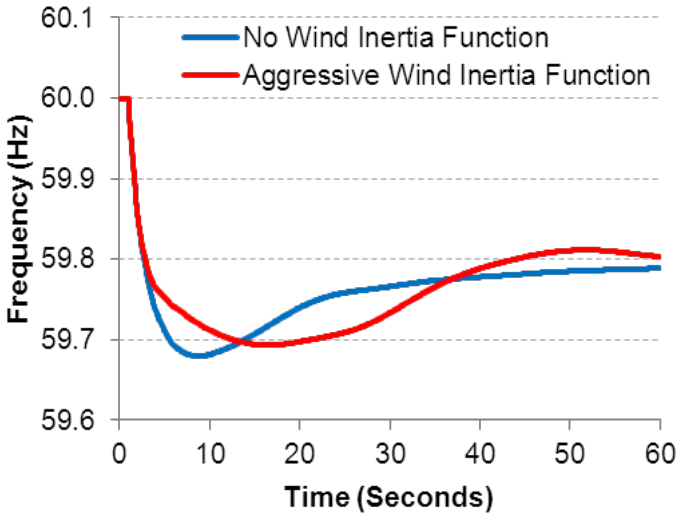
	Winter Low Load – High WECC Wind Case - Practical Minimum Headroom			Winter Low Load – High WECC Wind Case – Practical Minimum Headroom – Reduced Governor Withdrawal		
	WECC	CA	Non-CA	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.56	59.55	59.55	59.58	59.57	59.57
Frequency Nadir Time (Seconds)	13.4	14.6	13.4	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

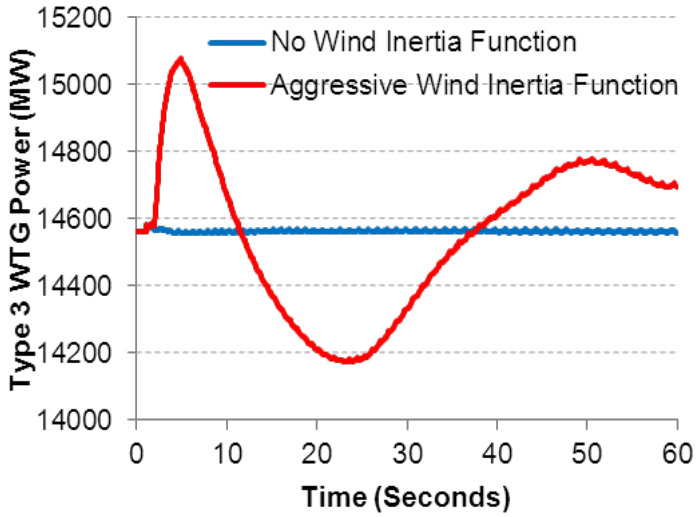
Mitigation Measures – Inertial Response From Wind Plant

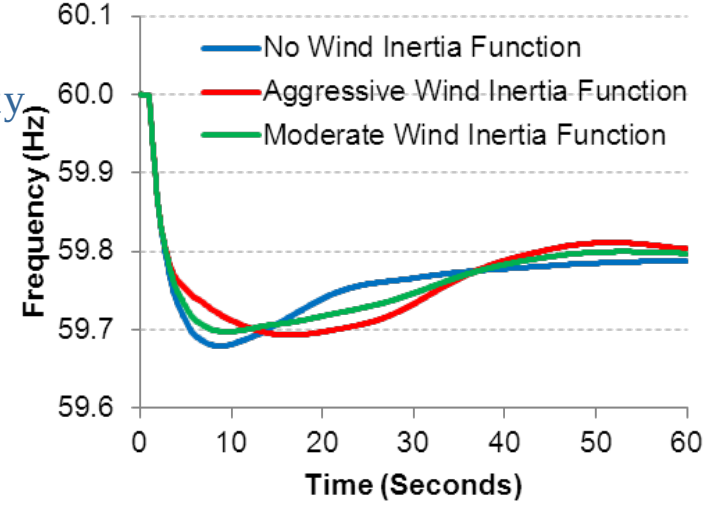
Winter Low Load – High WECC Wind case

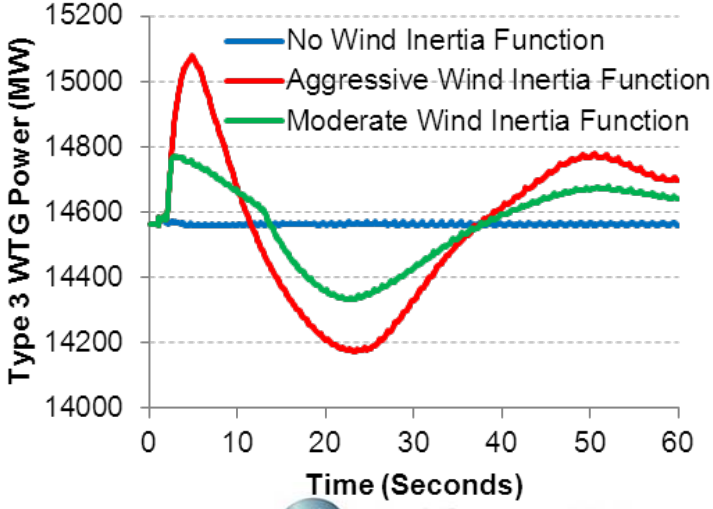
all of the type 3 wind turbine machines, with a total power output of 14600 MW (out of a total of 18094 MW wind for the case) are assumed to have an inertial control.

The ability to tune inertial controls presents an opportunity to improve system performance.





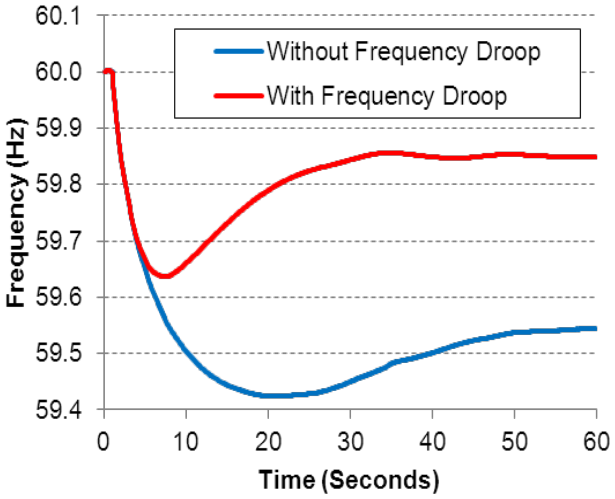


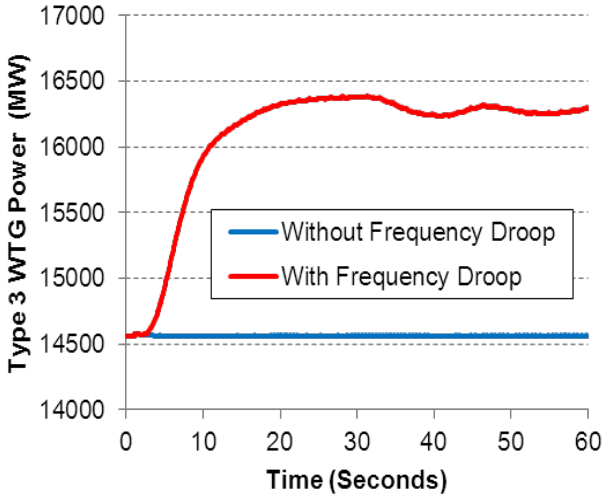


Mitigation Measures – Governor Response (Frequency Droop) from Wind Plants

Winter Low Load – High WECC Wind Case – Extreme Minimum Spinning Reserves

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.





Primary frequency response from wind generation has the potential to greatly improve system frequency performance of the entire WECC grid.

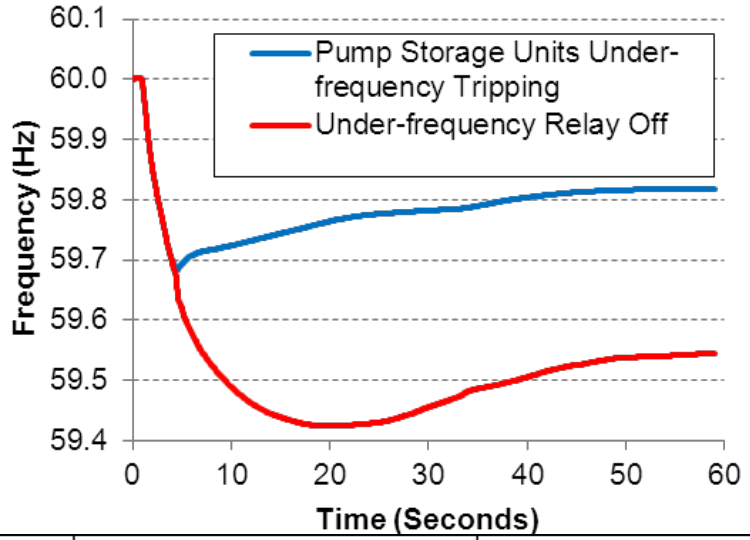
The California contribution to frequency response goes from an unacceptable 152 MW/0.1 Hz to a healthy 258 MW/0.1 Hz.

	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

Mitigation Measures – Load Control/Fast Energy Storage

Raised the tripping threshold of pumps and pumped storage hydro plants to 59.7 Hz.

Tripping of 1379 MW of pump motor load immediately arrests the frequency decline.



	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

Outline

- Study Objectives
- Development of Study Database and Performance Metrics
- Frequency Response of Base Cases
- Frequency Response of High Renewable Penetration Cases
- Factors Affecting Frequency Response
- Mitigation Measures
- Conclusions

Conclusions

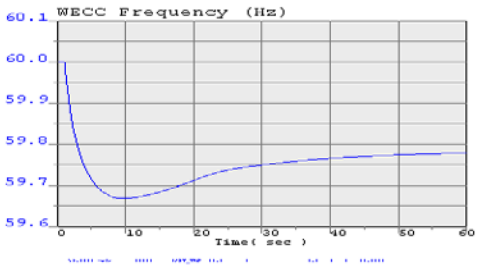
- Frequency Response is not in crisis for California
- Secondary reserves need to be adequate.
- No UFLS action in the Base Case Simulations
- Renewable penetration outside of California is important
- California's response generally meets its FRO depending on system conditions.
- Kt is a good primary metric
- Kt alone does not give all the necessary information…headroom is important
- Speed of primary response is important
- Governor Withdrawal has a detrimental impact on frequency response
- Impact of reduced System Inertia on initial rate-of-change-of-frequency does not appear to be important.
- Inertial controls from Wind Generation help
- Results are largely consistent with LBNL predictions
- Participation of renewables in providing frequency response is beneficial
- Load control can be used to improve frequency response
- Fast acting Energy Storage will provide significant benefits
- Market mechanisms will likely be necessary to assure adequate frequency response in future and under all operating conditions

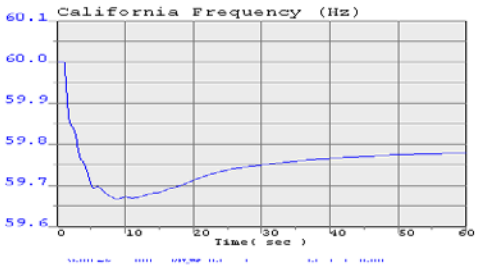
THANK YOU

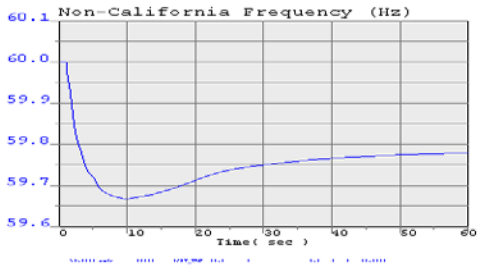
nicholas.miller@ge.com

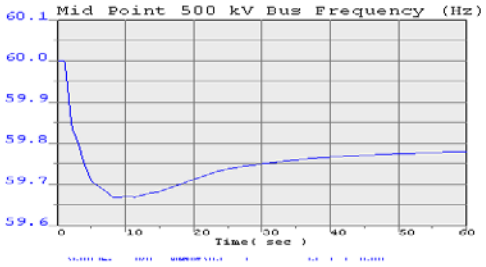
Additional Results and Materials

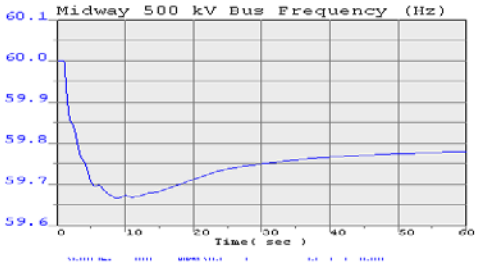
Frequency Behavior – Selected 500 kV Bus

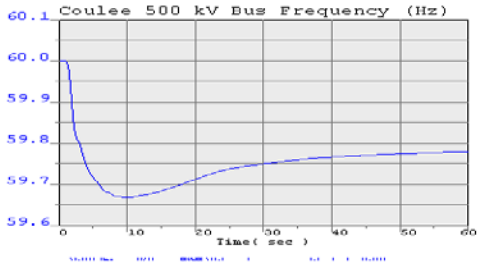


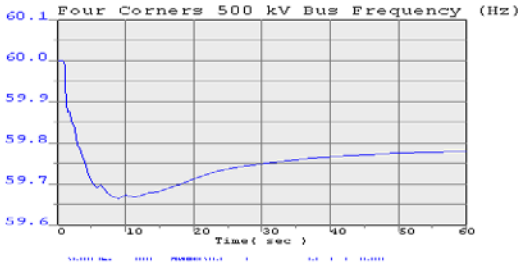


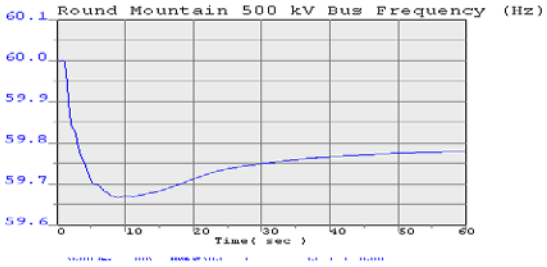


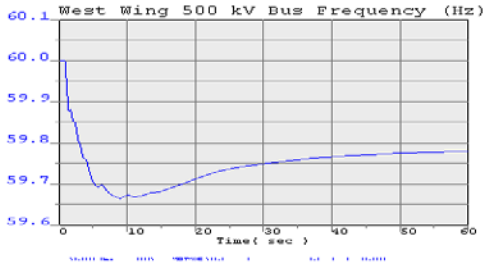


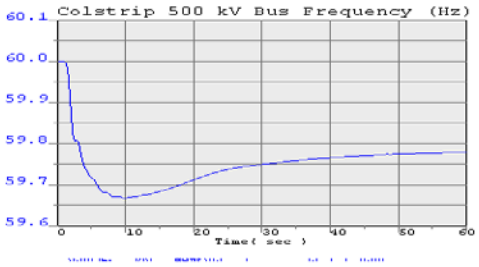


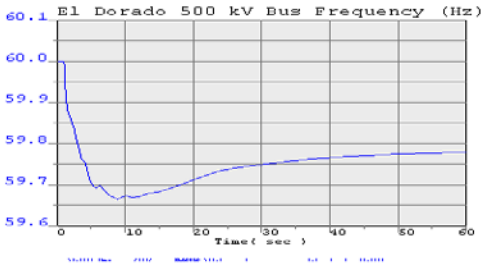


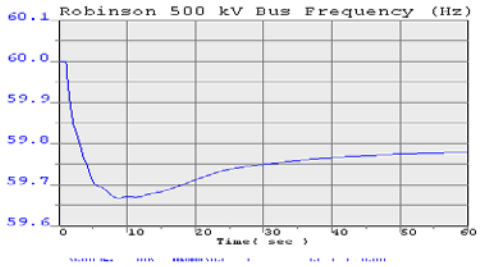






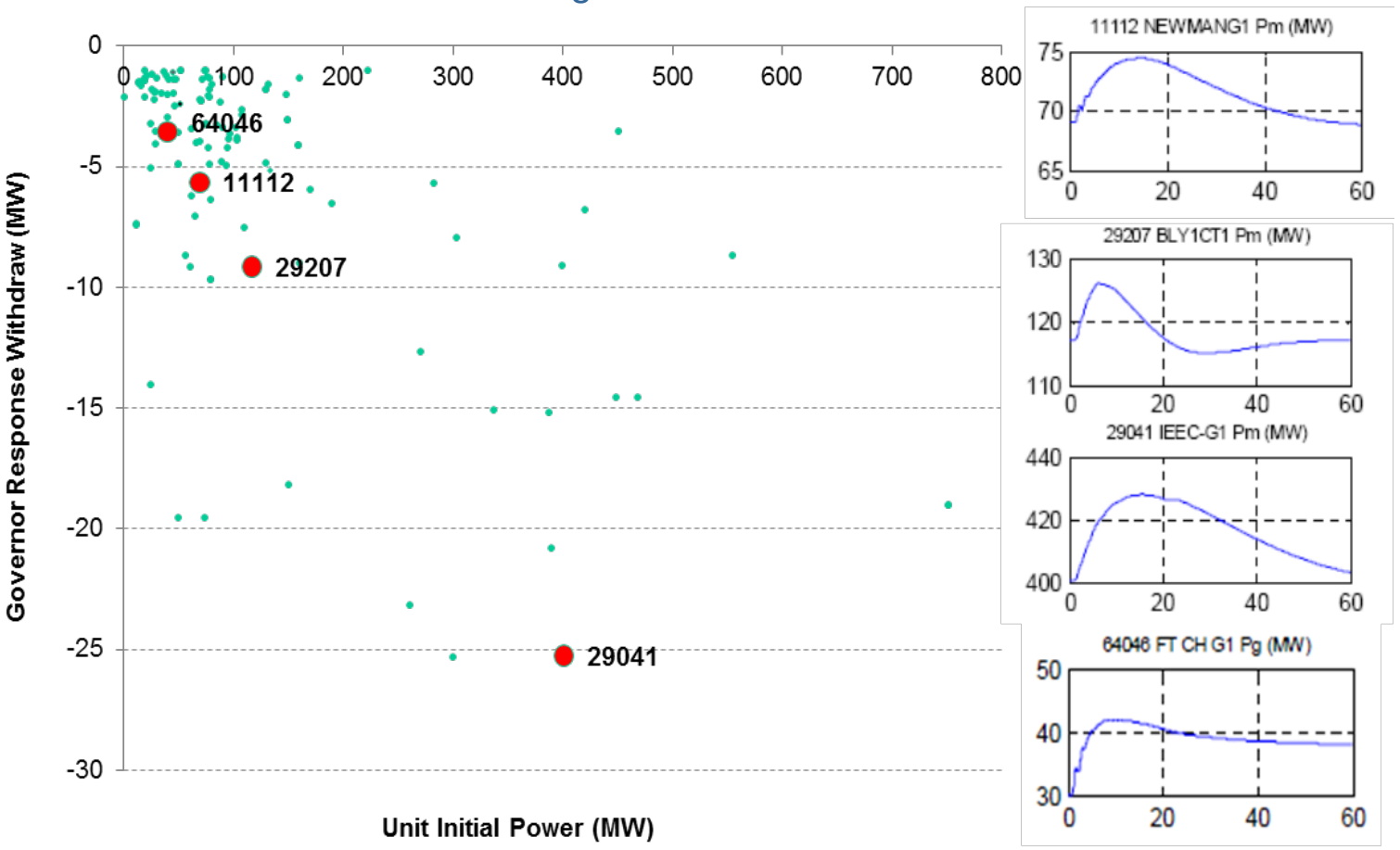






Governor Response Discussion - Governor Withdrawal

Winter Low Load – High CAISO Wind Base Case

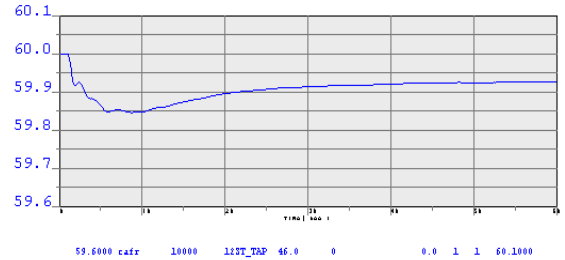


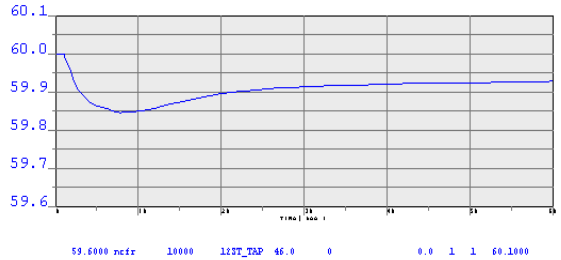
"Withdrawal" - any machine that is producing less power at 60 seconds than it did at any point earlier in the simulation

"Withdrawal Power" - the difference between the peak post-disturbance output, and the output at the end of the simulation

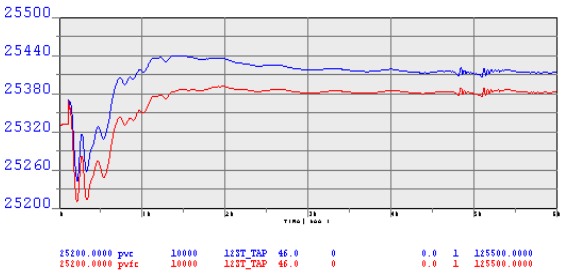
Single Palo Verde Unit Trip Event (1345 MW) - Load Voltage and Frequency Response

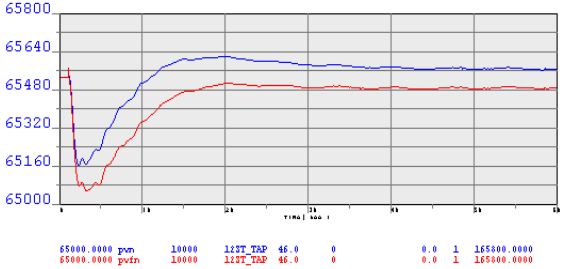
Frequency



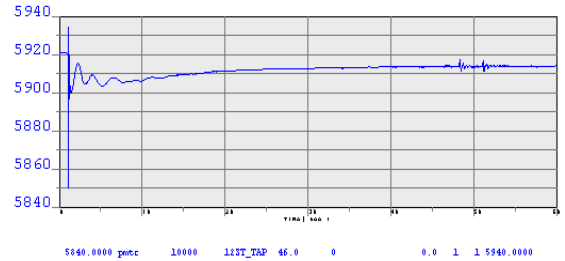


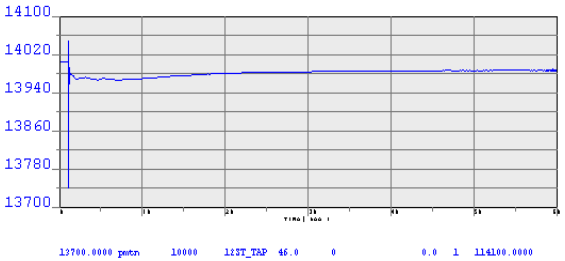
Blue curve - voltage dependent static load.
Red curve - voltage and frequency dependent static load



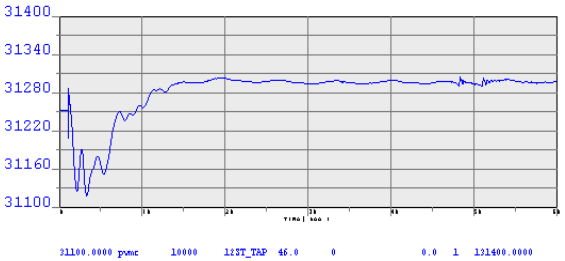


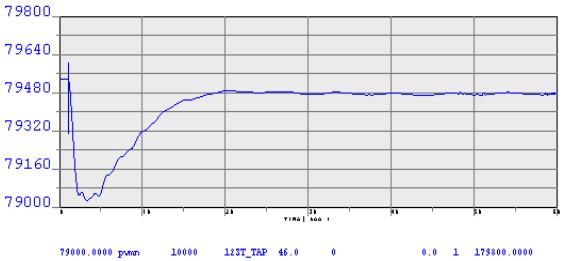
Dynamic Load



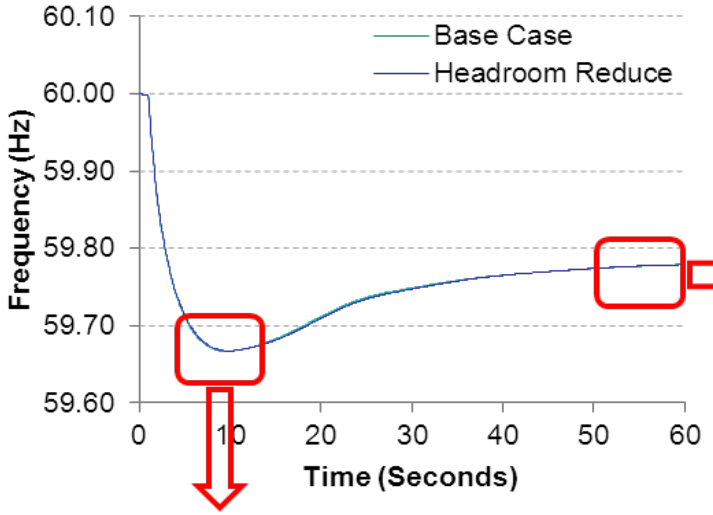


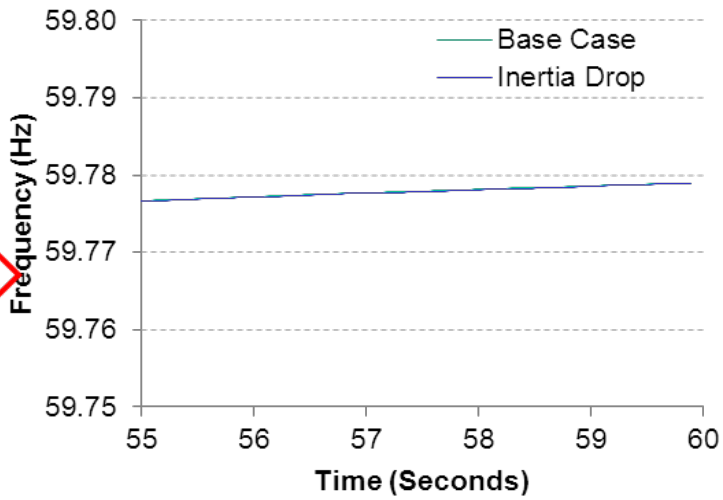
Total load

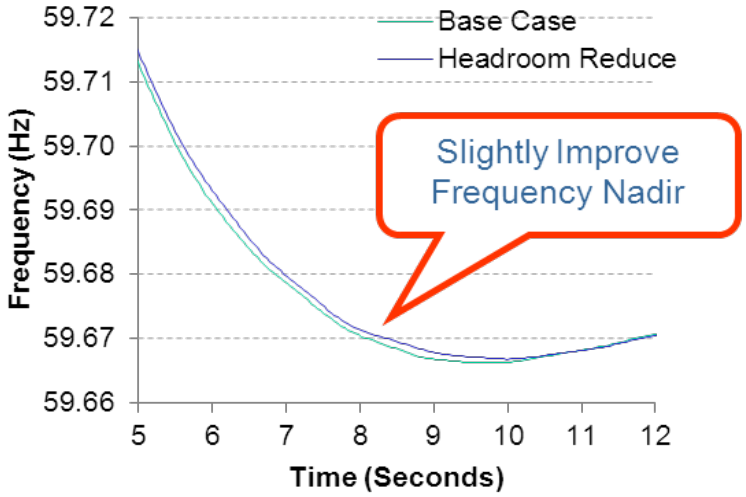




Reduce Headroom - Small Change in Headroom







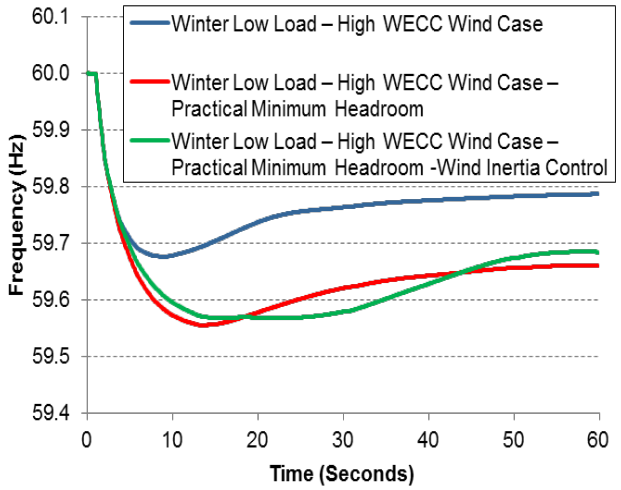
Base case – 13724 MW Headroom
Reduce headroom case – 11739 MW Headroom

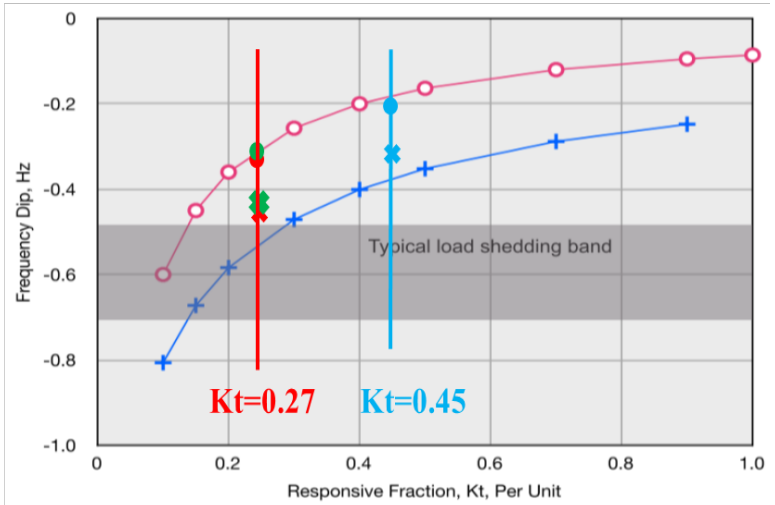
- 19 GR units, with total dispatch of 3105 MW and rating (MWCAP) of 5688 MW were selected dispatched up 1981.
- 6 base load units, with total dispatch of 2081, were selected to dispatched up 1981 MW.
- Reduce the headroom by 1981 MW.

Headroom only matters if it becomes scarce

Mitigation Measures – Inertial Response From Wind Plant

High WECC Wind Case – Practical Minimum Spinning Reserves





Frequency nadir and settling frequency are improved.

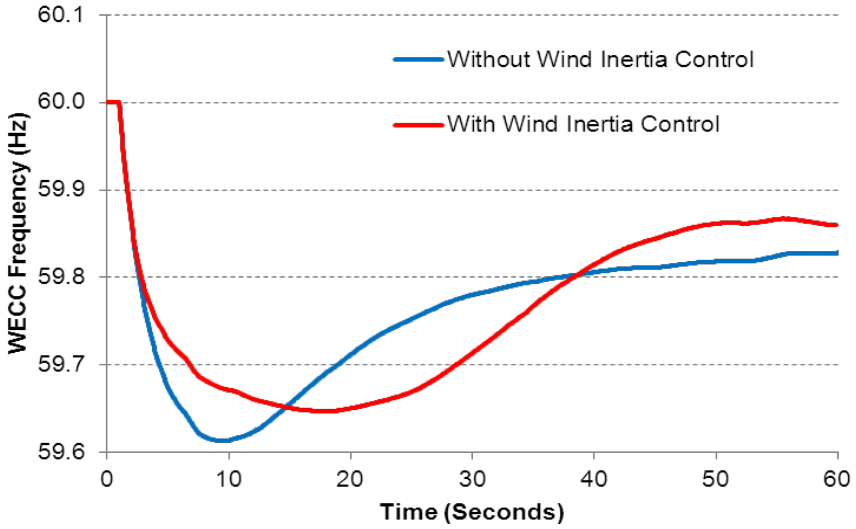
Inertia control has relatively little benefit for system that have limited headroom.

	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

Mitigation Measures – Inertial Response From Wind Plant

Weekend Morning – High WECC Wind and Solar Case

Inertial controls can give a significant benefit in terms of improving margin above UFLS, even for stressed conditions.

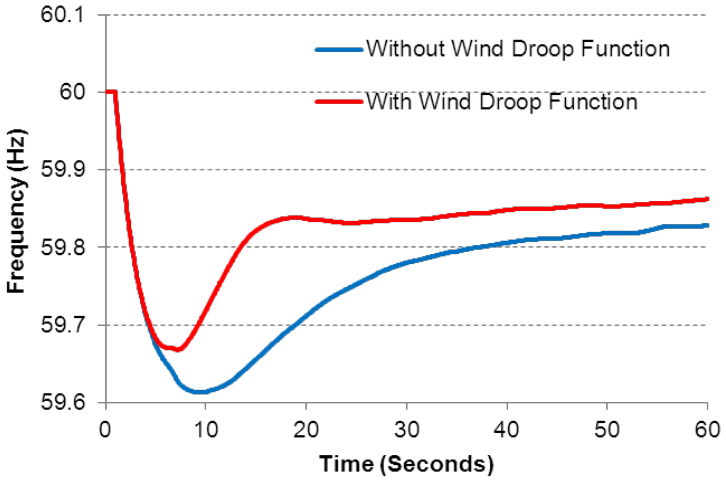


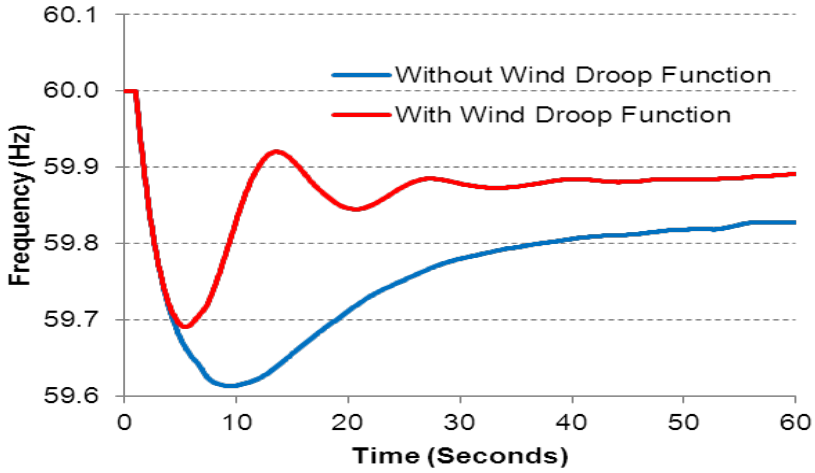
Roughly 20% improvement in the nadir-based frequency response metric

	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

Mitigation Measures – Governor Response (Frequency Droop) from Wind Plants

Weekend Morning – High WECC Wind and Solar Case

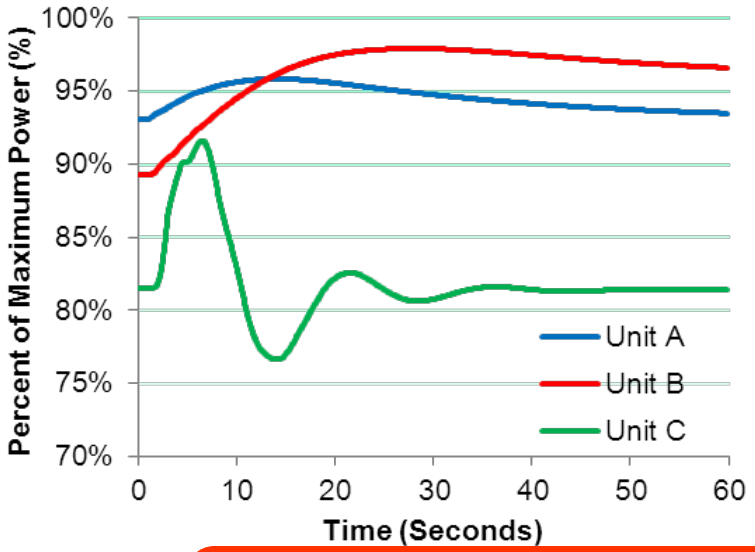


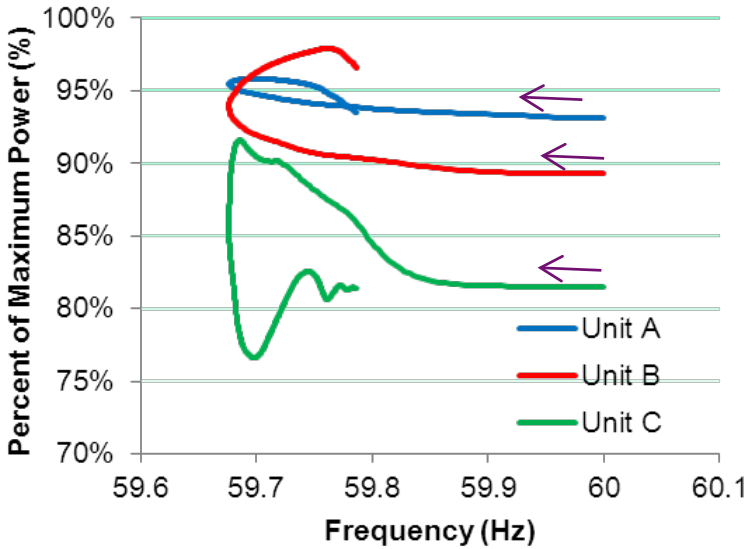


	Weekend Morning – High WECC Wind and Solar Case			Weekend Morning – High WECC Wind and Solar Case – Frequency Droop			Weekend Morning – High WECC Wind and Solar Case – Frequency Droop		
	WECC	CA	Non-CA	WECC	CA	Non-CA	WECC	CA	Non-CA
Frequency Nadir (Hz)	59.61	59.61	59.61	59.67	59.65	59.67	59.69	59.67	59.67
Frequency Nadir Time (Seconds)	9.7	9.9	9.1	7.2	5.7	7.2	5.4	5.6	5.6
LBNL-Nadir Based Frequency Response (MW/0.1Hz)	695	684	697	810	770	815	870	813	838
GE-CAISO Nadir Based Frequency Response (MW/0.1Hz)	515	140	354	629	99	519	536	104	423
Percent of Total (%)		27.0	59		15.7	82.5		19.4	78.9
Settling Frequency (Hz)	59.83	59.82	59.83	59.86	59.86	59.86	59.89	59.89	59.89
NERC Frequency Response (MW/0.1Hz)	1565	1520	1578	1947	1881	1921	2471	2365	2365
GE-CAISO Settling Based Frequency Response (MW/0.1Hz)	1158	311	802	1510	243	1257	1522	302	1232
Percent of Total (%)		27.0	69.0		16.1	83.3		19.8	81.0

Governor Response Discussion - Comparison of Response

Winter Low Load – High CAISO Wind Base Case





Units with initial generation greater than 300 MW