Western Wind and Solar Integration Study Phase 3 – Frequency Response and Transient Stability: Executive Summary

N.W. Miller, M. Shao, S. Pajic, and R. D'Aquila
GE Energy Management
Schenectady, New York

NREL Technical Monitor: Kara Clark

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NREL regrets any inadvertent omission of any project participants and contributors.

Abbreviations and Acronyms

AC	alternating current
COI	California-Oregon Interface
CSP	concentrating solar thermal power
DC	direct current
DG	distributed generation, embedded PV
FR	frequency response
FRO	frequency response obligation
GR	governor response
GW	gigawatt
Hz	Hertz
IFRO	interconnection frequency response obligation
MVA	megavolt ampere
MW	megawatt
NERC	North American Electric Reliability Corporation
PDCI	Pacific DC Intertie
PV	photovoltaic solar power, utility-scale photovoltaic power plant
RAS	remedial action scheme
ROCOF	rate of change of frequency
s	second
UFLS	under-frequency load shedding
WECC	Western Electricity Coordinating Council
WWSIS	Western Wind and Solar Integration Study

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Introduction

All of the large-scale regional wind and solar integration studies performed by the National Renewable Energy Laboratory (NREL) and others have identified the lack of power system dynamic analysis as a significant research gap. Acceptable dynamic performance of the grid in the fractions of a second to one minute following a large disturbance (e.g., loss of a large power plant or a major transmission line) is critical to system reliability, thus there is a need to analyze the dynamic behavior of North American systems under high variable renewable conditions. The Western Interconnection, in particular, has a long history of dynamic performance constraints on system operation—so any dynamic performance changes due to increased wind and solar generation could have substantial impact on all aspects of renewable integration. The primary objectives of Phase 3 of the Western Wind and Solar Integration Study (WWSIS-3) are to examine the large-scale transient stability and frequency response of the Western Interconnection with high wind and solar penetration, and to identify means to mitigate any adverse performance impacts via transmission reinforcements, storage, advanced control capabilities, or other alternatives.

WWSIS-3 evaluated a variety of system conditions, disturbances, locations, and renewable penetration levels to help draw broader conclusions from an analysis of two specific types of power system stability: frequency stability and transient stability. A technical definition of the different aspects of power system stability is provided in (Kundur et al. 2004). Less technical descriptions of both frequency and transient stability are provided in the following sections of this report.

Frequency Stability Background

To reliably operate a large, interconnected power grid such as the Western Interconnection (shown in Figure 1) requires a constant balancing of electricity generation with electricity demand. Electricity must be generated at the same instant it is used, so operating procedures have developed to forecast electricity demand, schedule electric generators to meet that demand, and ensure sufficient generating reserves are available to respond to forecast errors and system disturbances. The measure of success in this balancing act is frequency. In North America, that means maintaining system frequency at or very close to 60 Hz, as shown in Figure 2.

However, disturbances do occur, including large ones that affect overall system frequency (e.g., abrupt outage of a large generator or a major transmission line). For example, a transmission line outage may disconnect a large industrial customer, and as a result, the total electricity generation exceeds the total electricity demand, and frequency rises. Because operators, in general, have more control over generation than demand, they can execute a generation reduction to regain the balance and return system frequency to near 60 Hz.

A potentially more significant problem is the loss of a large generating plant. As a result of this type of disturbance, the total electricity demand exceeds the total electricity generated and frequency drops, as shown in Figure 3. In general, a power grid is designed to withstand the loss of the single largest generator. However, the loss of multiple generators or plants may cause the frequency to drop significantly such that protective devices act to disconnect customers in order to preserve the bulk of the system. It is a serious reliability failure when operators lose the ability to supply all the electricity needed to meet demand.

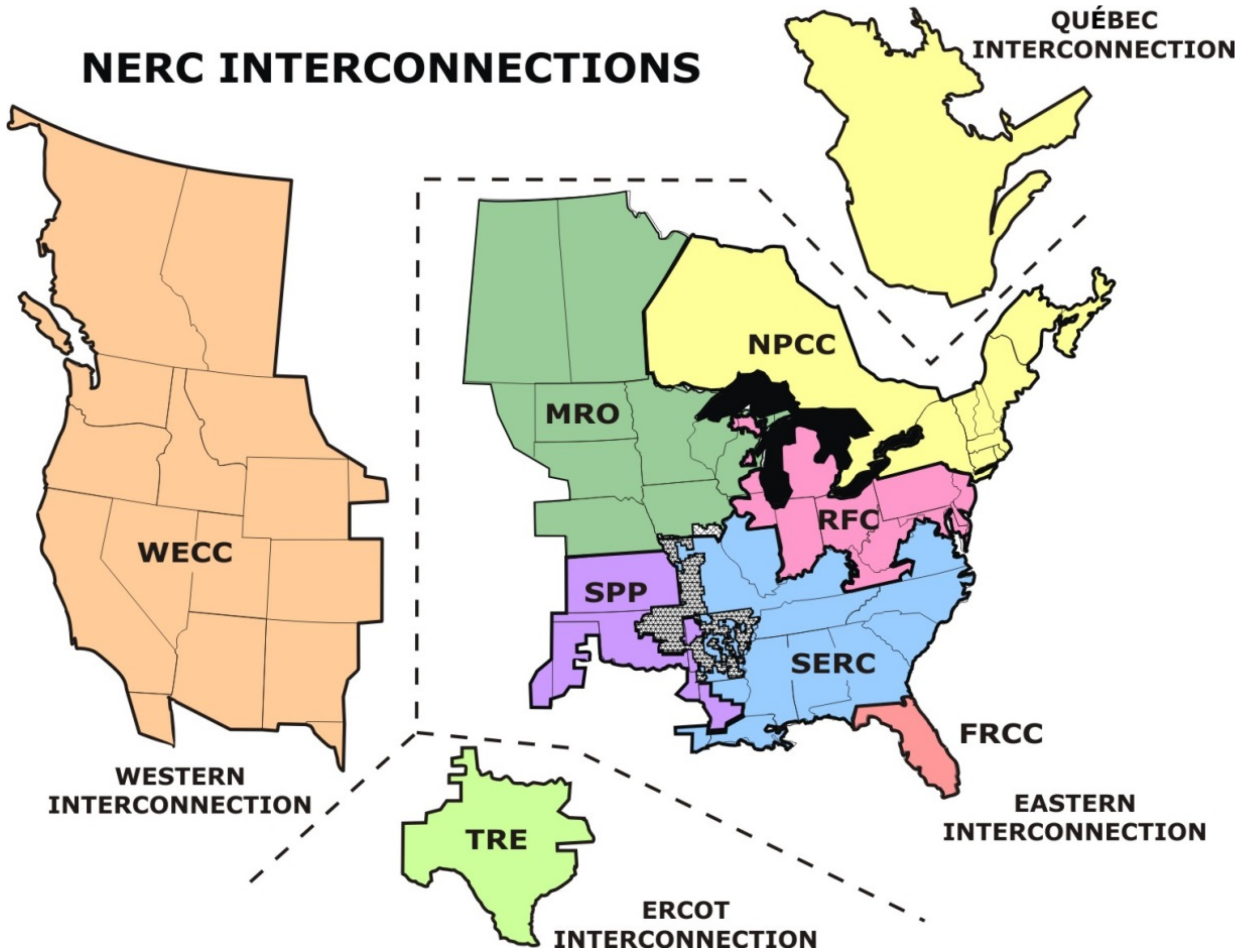

Figure 1. North American electricity grid interconnections.[1]

[1] http://www.nerc.com/AboutNERC/keyplayers/Documents/NERC_Interconnections_Color_072512.jpg

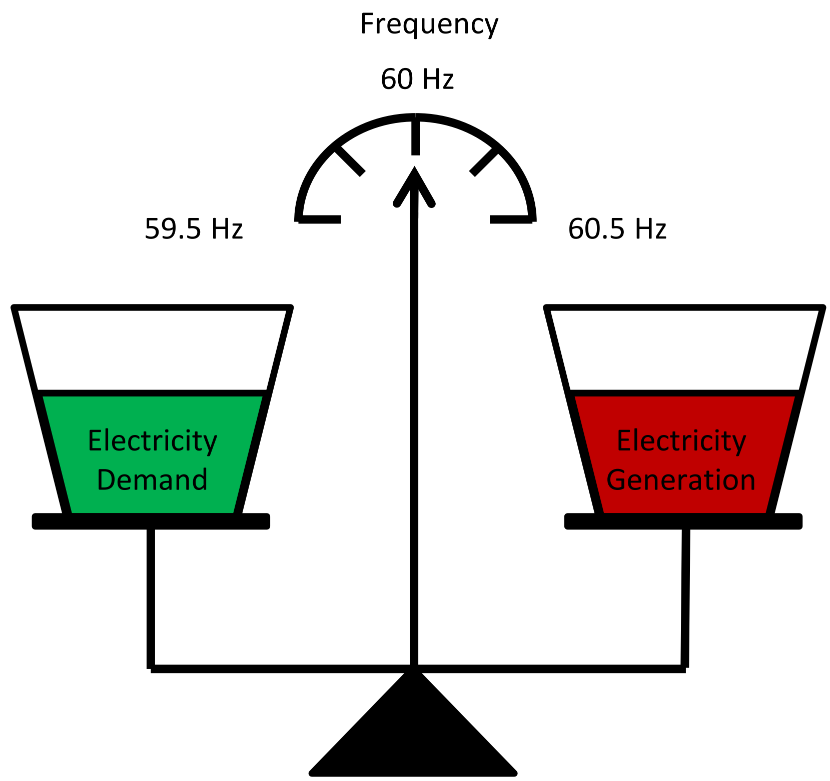

Figure 2. Balance analogy for frequency stability.

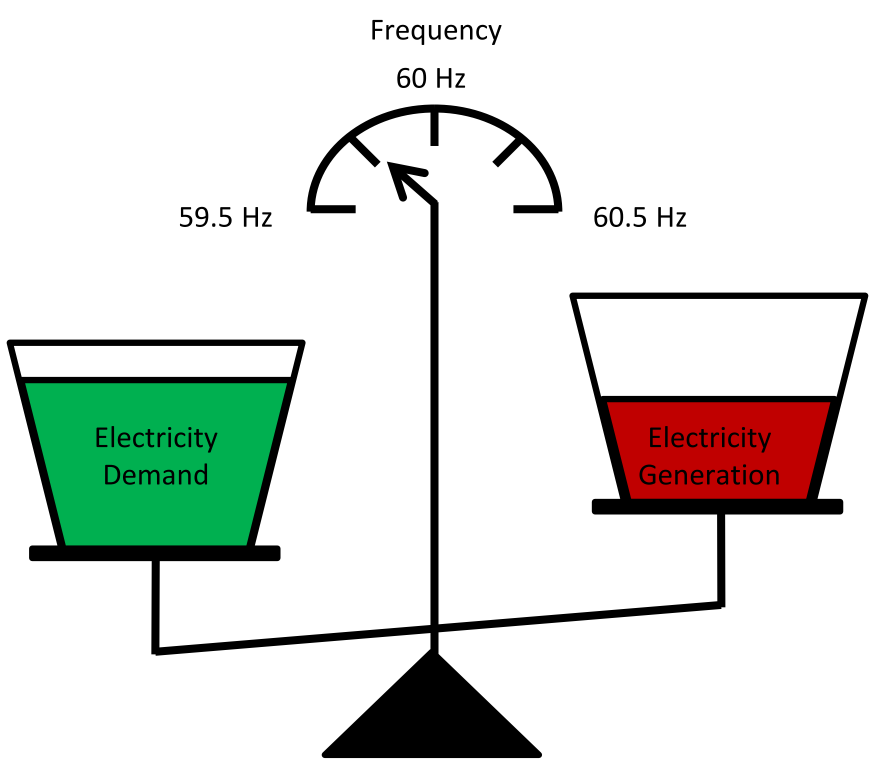

Figure 3. Electricity demand exceeds electricity generation, and frequency drops.

An example of system frequency in response to a large generation trip is shown in Figure 4. The system is operating normally, with a frequency of 60 Hz, up to 1 second. At that time, a large generating unit is abruptly lost. Load now exceeds generation, so the frequency drops. The speed of the initial decline is related to the number of conventional synchronous generators on the system. More generators mean more inertia, which retards the frequency decline. At about 10 seconds, the frequency nadir or minimum is reached. Frequency nadir is one measure of a system's frequency stability—it must be above the highest level of under-frequency load shedding. At that point in time, the generators with governor controls have begun to act to increase power output, and thus the system frequency begins to recover. By about 60 seconds, the system frequency has settled out somewhat below the normal operating frequency of 60 Hz. Another metric of frequency stability is based on the change in frequency between the nadir and this settling frequency, and the change in power between these two points in time. This is called frequency response (FR) and is formally defined by the North American Electric Reliability Corporation or NERC (NERC 2012). After 60 seconds, even more generators begin to increase their power output, and the frequency returns to normal within about 10 minutes. One part of WWSIS-3 focuses on system frequency behavior in the first 60 seconds following an outage.

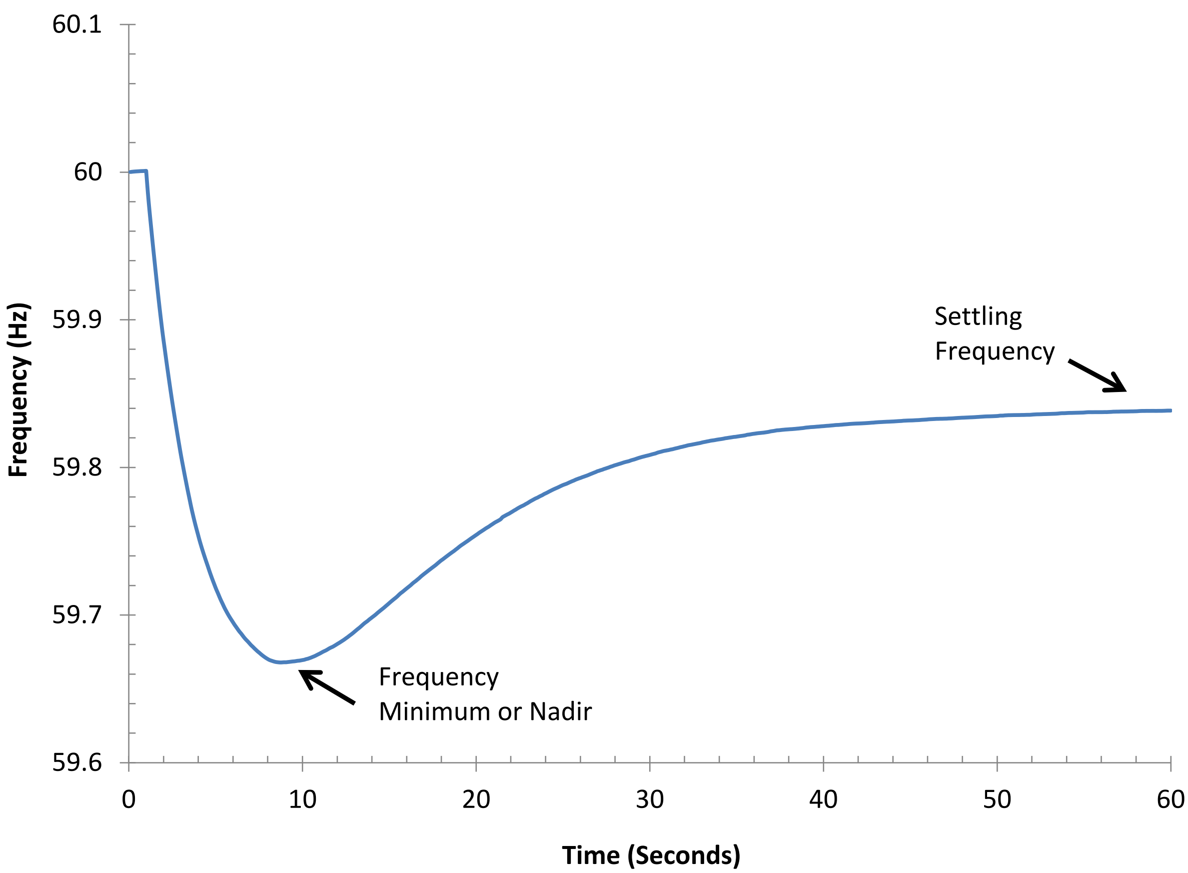

Figure 4. System frequency in response to a large generation trip.

There is general concern among power system operators and utilities regarding the degradation of FR in North America over the past two decades. The decline is due to various factors, including the withdrawal of primary or governor response (GR) shortly after an event, the lack of in-service governors on conventional generation, and the unknown and changing nature of load frequency characteristics. Large penetrations of inverter-based, or non-synchronous, generation technologies further complicate this issue. Without special operation or controls, wind and solar plants do not inherently participate in the regulation of grid frequency. By contrast, synchronous machines always contribute to system inertia, and some fraction of the synchronous generation in operation at any point has governor controls enabled. When wind and solar generation displaces conventional synchronous generation, the mix of the remaining synchronous generators changes and has the potential to adversely impact overall FR.

Therefore, one of the primary objectives of WWSIS-3 is to evaluate and to better understand the impact of high penetrations of wind and solar power on system-wide FR to large generator outages in the first minute after the outage occurs.

Transient Stability Background

In addition to maintaining the balance between electricity generation and electricity demand, power system operators must ensure that the grid can successfully transition from normal operation (e.g., all transmission lines and generating units are in service), through a disturbance (e.g., abrupt outage of a major transmission line or large generator), and into a new stable operating condition in the 10–20 seconds immediately following a disturbance. The ability to make this successful transition is called transient stability, and is an even faster phenomenon than frequency stability.

A mechanical analogy for transient stability is illustrated by Figure 5 (Vittal 2003). Imagine a set of balls of different sizes connected to each other by a set of breakable elastic strings. The balls represent generators of different sizes and characteristics, and the strings represent the interconnecting transmission lines. The system is disturbed when one of the balls is hit with a stick. The ball begins to swing, and the string connected to the ball also swings. Other strings follow suit, and other balls start to swing. As a result of the single disturbance, the entire system of strings and balls is moving in response. If the swings die down, and the system comes back to rest, then the system is transiently stable. On the other hand, if the swings grow, one or more balls may break away from the rest, and the system is transiently unstable.

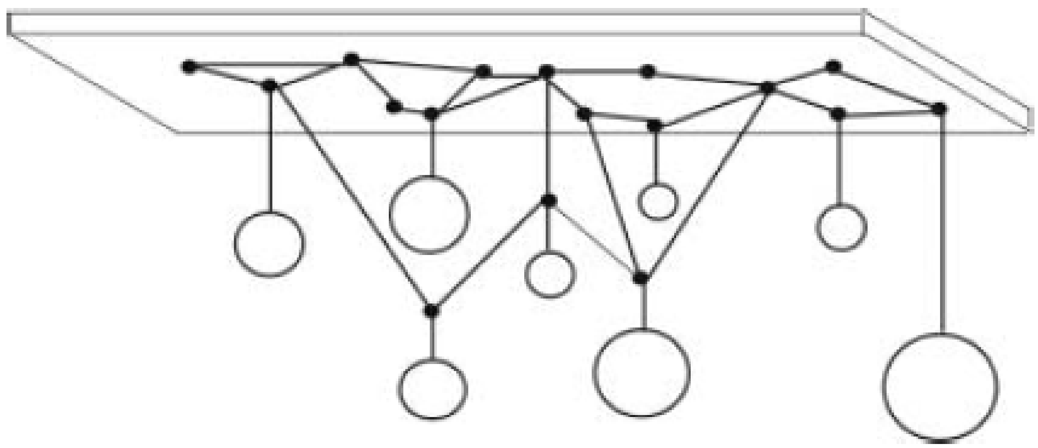

Figure 5. Mechanical analogy for transient stability (Vittal 2003).

An example of both transient stability (blue) and transient instability (red) is shown in Figure 6. The system is operating normally, with a transmission substation voltage of 100%, up to 0.5 seconds. At that time, a disturbance occurs, such as a tree falling on a transmission line. From 0.5 seconds to 0.7 seconds, the voltage is zero because the tree is connecting the transmission line to the ground. At about 0.7 seconds, an automatic protection system trips the transmission line, and the voltage returns to near normal—but as described above, the system is swinging in response to the disturbance. When the swings grow and the system separates, the substation voltage drops precipitously, and the system collapses at about 1 second. When the swings die down, the substation voltage settles back to normal within 5 seconds. The second part of WWSIS-3 focuses on system stability in the first 5–10 seconds.

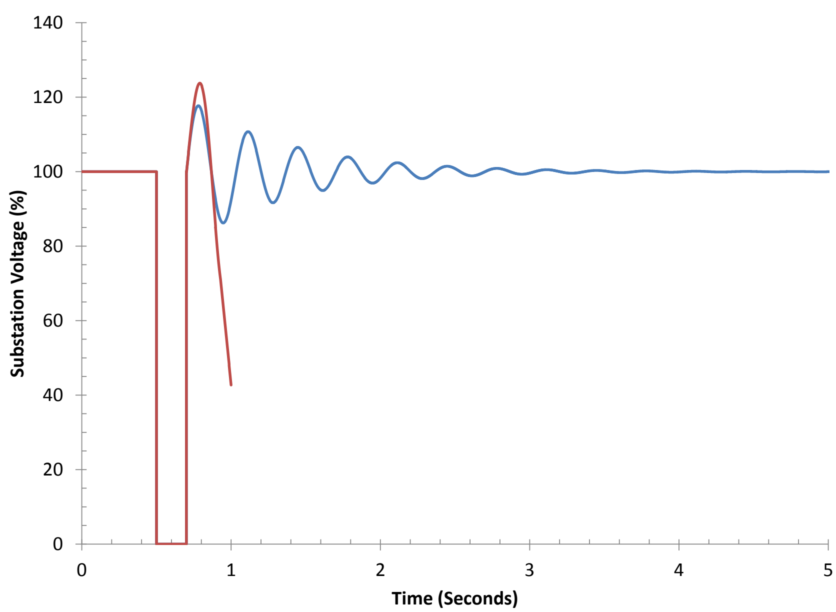

Figure 6. Substation voltage in response to transmission system disturbance.

As noted, the Western Interconnection has a long history of constraints due to transient stability limitations that vary depending on system characteristics such as the level of electricity demand (e.g., peak summer load), the amount of power flowing on the transmission system (e.g., heavy flows on critical paths), and the location of generating plants in operation (e.g., remote from population centers). One of the primary objectives of WWSIS-3 is thus to evaluate and better understand the impact of high penetrations of wind and solar power on the large-scale transient stability of the Western Interconnection. The primary measures of transient stability are avoiding bulk system separation and individual generator loss of synchronism with the system, and meeting various voltage and frequency swing criteria, which vary with the severity of the disturbance according to NERC and Western Electricity Coordinating Council (WECC) reliability standards.

While transient stability can be both systemic and local, this study focuses on large-scale events that affect the security of the entire interconnection. Large penetrations of inverter-based, or non-synchronous, wind and solar generation may substantially alter system stability as a result of changes in angle/speed swing behavior due to reduced inertia, changes in voltage swing behavior due to different voltage control systems, different power flow patterns, and displacement of synchronous generation at key locations.

Study Scenarios

Transient stability and FR are dominated by the generation initial conditions. Thus, realistic and economically rational initial conditions are needed. The load flow that provides the starting point for dynamic simulations is a single snapshot in time and not, in itself, an economic tool. It is necessary to use economic tools to guide the commitment and dispatch process. Thus, the WWSIS-3 study scenarios leaned heavily on the work done for Phase 2 of the Western Wind and Solar Integration Study (WWSIS-2)—particularly the WWSIS-2 Hi-Mix scenario, which included 16.5% wind and 16.5% solar penetration on an annual energy basis. While the mapping between the WWSIS -2 system topology and the WWSIS-3 cases is good, it is not perfect. The studies used different analytical tools and different starting databases.

In particular, the following data were derived from WWSIS-2 for WWSIS-3:

- Wind and solar plant capacity and location data
- Total power production of wind and solar plants by area
- Change in commitment and dispatch of conventional generation plants between the Base case (with low levels of renewable generation) and the Hi-Mix case.

Transmission system upgrades from WWSIS-2 were not used in the primary WWSIS-3 analysis, but a limited number were used for a sensitivity analysis.

Four primary study scenarios were developed to represent different system conditions (i.e., light and heavy load) and different renewable penetration levels (i.e., base and high renewables). The main focus of WWSIS-3 was to understand the impact of increasing renewable power levels, which made the starting cases critical. After extensive stakeholder input, two well-established future WECC planning cases were selected, representing light spring and heavy summer load conditions. These cases include transmission system upgrades that the WECC stakeholders deemed likely within the next 10 years. However, no additional transmission system upgrades as identified by WWSIS II were used, except in the sensitivity analysis. Overall, this transmission system model gives a valuable reference, as both FR and transient stability concerns will tend to be improved by added transmission. If the system has acceptable dynamic performance, new transmission might still make economic sense, but it will not be needed to maintain stability and adequate FR even with high levels of wind and solar.

The study case development included improvements to the original WECC power flow and dynamic databases, as well as the addition of geographically appropriate wind and solar plants, a composite load model to allow for an appropriate representation of rooftop photovoltaics (PV), high renewable penetration levels (40–60 GW), and a detailed analysis of the WWSIS-2 production simulation results to determine de-commitment and re-dispatch procedures for the balance of the generation portfolio.

The two light load scenarios include a Base case that represents a future in which the current renewable portfolio standard (RPS) targets are met. The Hi-Mix case was built from the Base case, but with even higher levels of wind and solar. This case represents a snapshot in time—a windy, sunny morning in the spring from the WWSIS-2 High Mix scenario (33% combined wind and solar by energy on an annual basis). The details (e.g., renewable plant MW output and siting, re-dispatch/de-commitment of the conventional units, etc.) were mined from the WWSIS-2 PLEXOS High Mix results. Great care was exercised to capture the economically rational change in commitment and dispatch that would accompany the wind and solar displacement of other generation. Limited local transmission reinforcements (e.g., synchronous condensers, shunt compensation) were added when the high renewables over-stressed local areas, but no major transmission projects were added beyond those built into the original WECC cases. A further sensitivity case, called Light Spring Extreme, was developed for additional analysis. This case was based on the simultaneous extremes of the highest wind and solar generation, and a very low load level. An overview of the renewable generation for the light load scenarios is shown in Figure 7 through Figure 9, and Table 1. The rooftop PV is shown in blue and is distinguished from utility-scale PV in yellow by the label "DG" (for distributed generation).

Similarly, there are two heavy summer scenarios—one base case and one high renewable case. Again, the Heavy Summer Base case represents a future in which the RPS targets are met, but for a snapshot in time when the production of wind and solar is relatively low. The Heavy Summer Hi-Mix case was again mined from the PLEXOS High Mix results from WWSIS-2 and represents a high wind and solar condition that might occur during a summer high load day. As would be expected, the instantaneous production of wind, even with a similar installed fleet, is rather less than the spring case. An overview of the renewable generation for the heavy load scenarios is shown in Figure 10, Figure 11, and Table 1. The table shows power production levels for the snapshot in time represented by the cases, not the collective rating or capacity of the installed renewables. Similarly, the percent penetration is the instantaneous penetration, not an annual average.

For the dynamic simulations, all new wind plants were modeled as Type 3 doubly fed asynchronous machines with voltage regulation and low-voltage ride through (LVRT), all new concentrating solar power (CSP) plants were modeled as synchronous machines without GR, all new utility-scale PV plants were modeled as full converter asynchronous machines with voltage regulation and LVRT, and all new distributed PV is modeled using the WECC composite load model.

The composite load model provides not only a means to model distributed PV—it allows for a more detailed model of the distribution system than is usual in a transmission-level study. In particular, this model also includes a substation transformer, distribution line, and four types of motor models, an electronic load, and a static load. This gives an overall load model for the Western Interconnection that has a higher proportion of motors than traditional studies, which will have a significant impact on the simulation results. Load modeling is a complex issue for both utility planners and researchers.

The primary tool in this work is GE's PSLF software package—a commercial power flow and transient stability simulation tool.

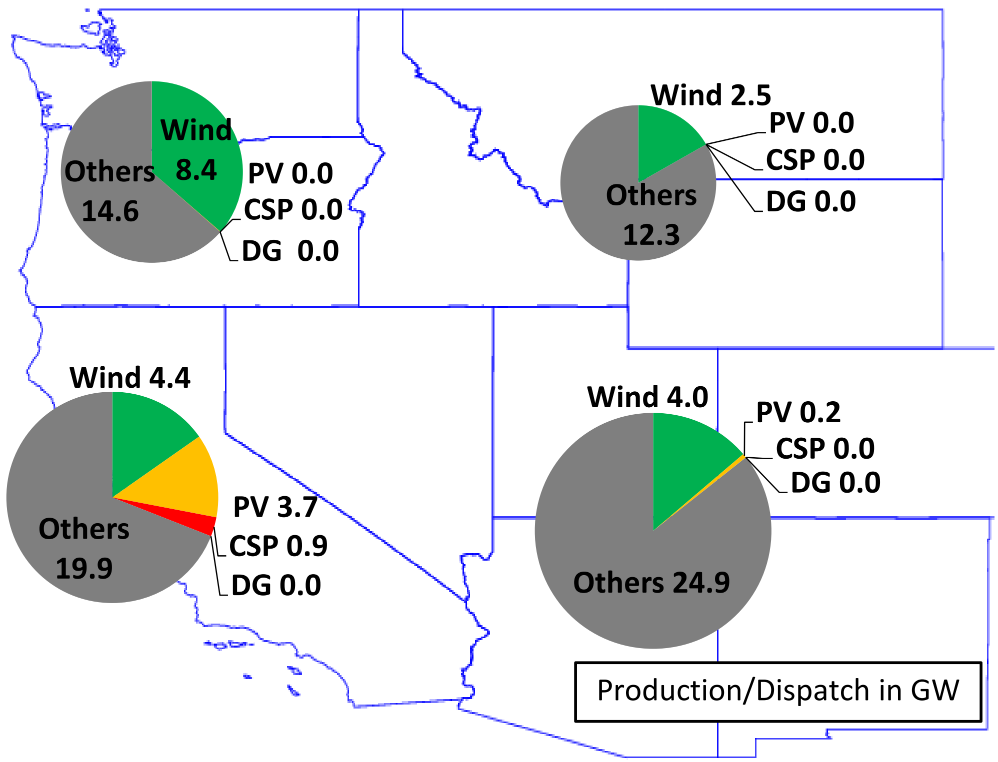

Figure 7. Wind and solar generation in the Light Spring Base case.

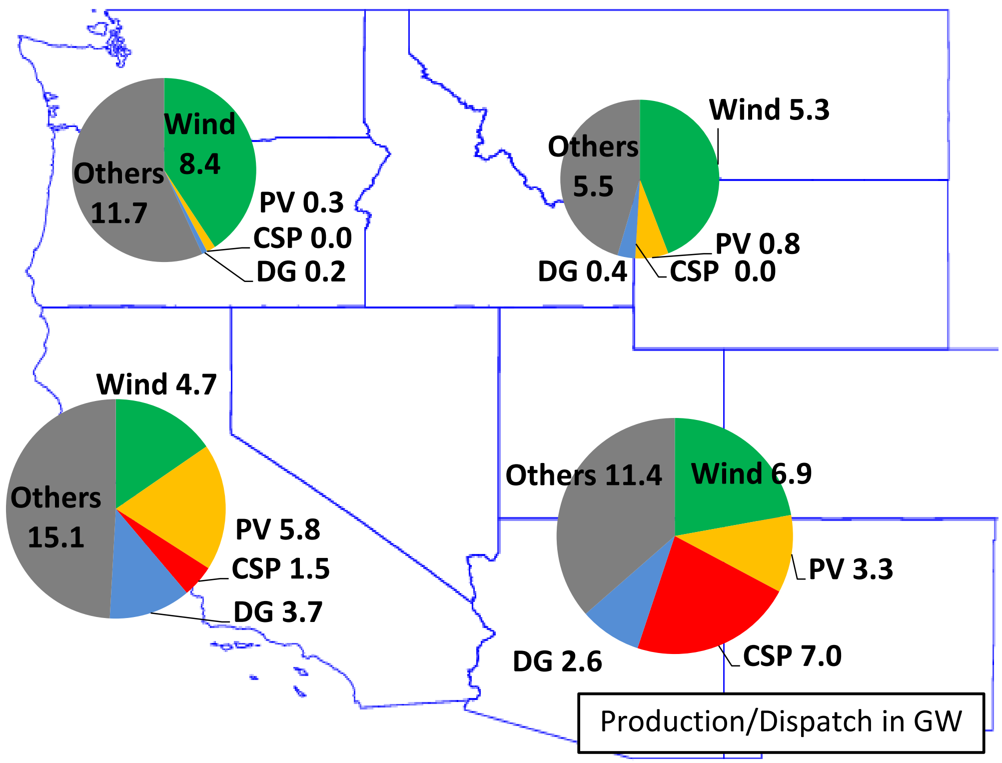

Figure 8. Wind and solar generation in the Light Spring Hi-Mix case.

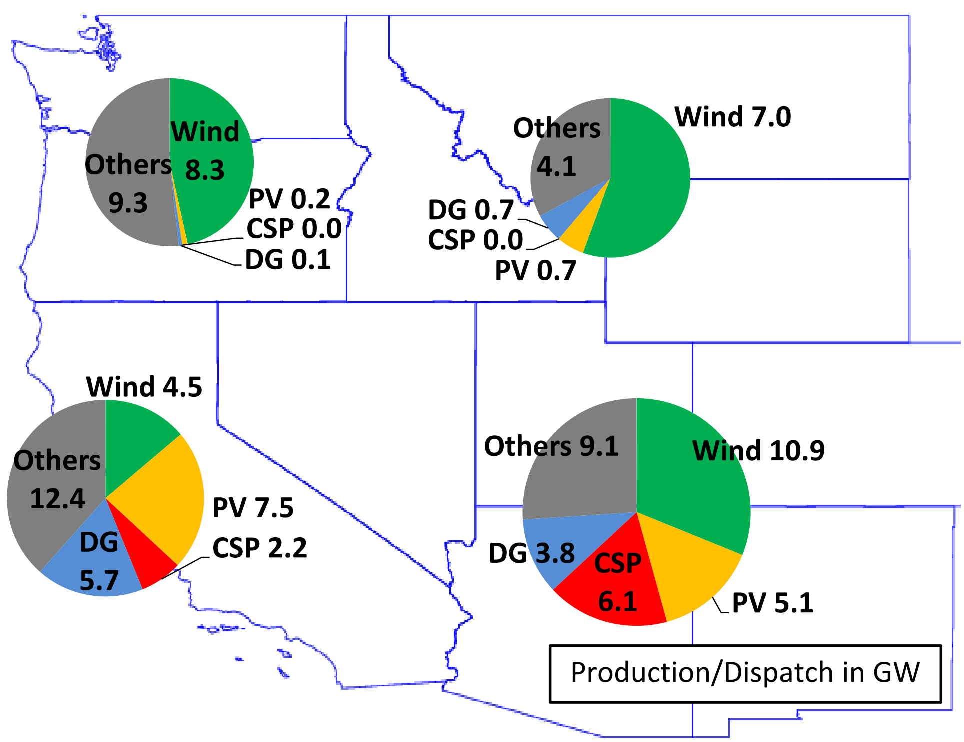

Figure 9. Wind and solar generation in the Light Spring Extreme case.

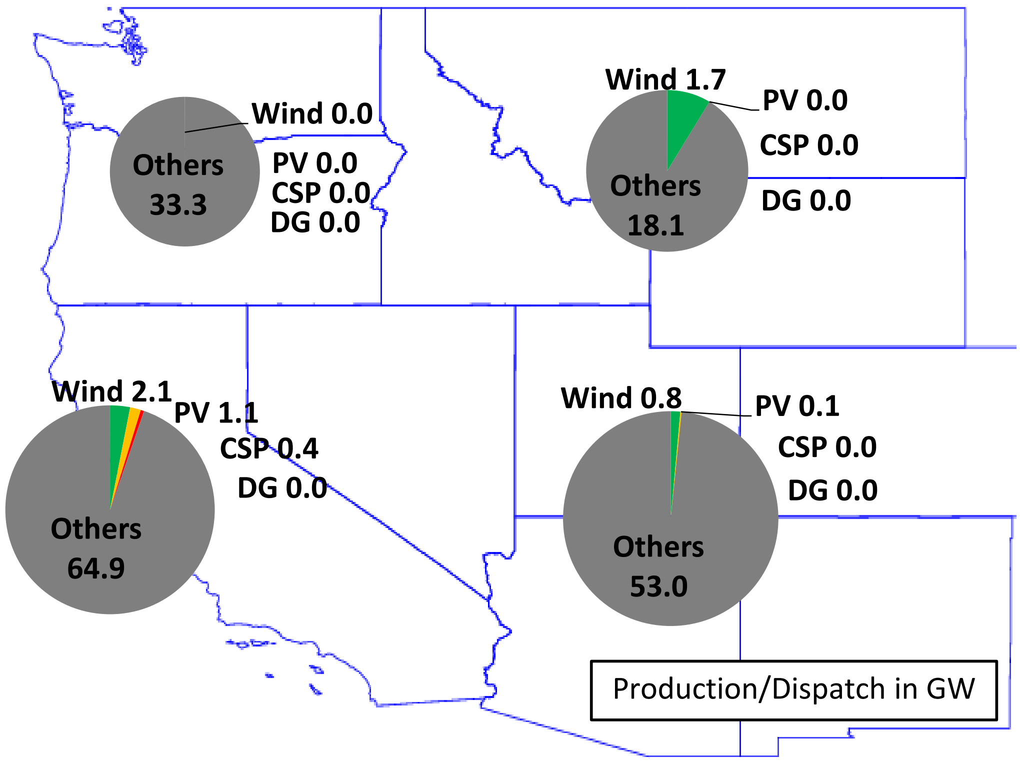

Figure 10. Wind and solar generation in the Heavy Summer Base case.

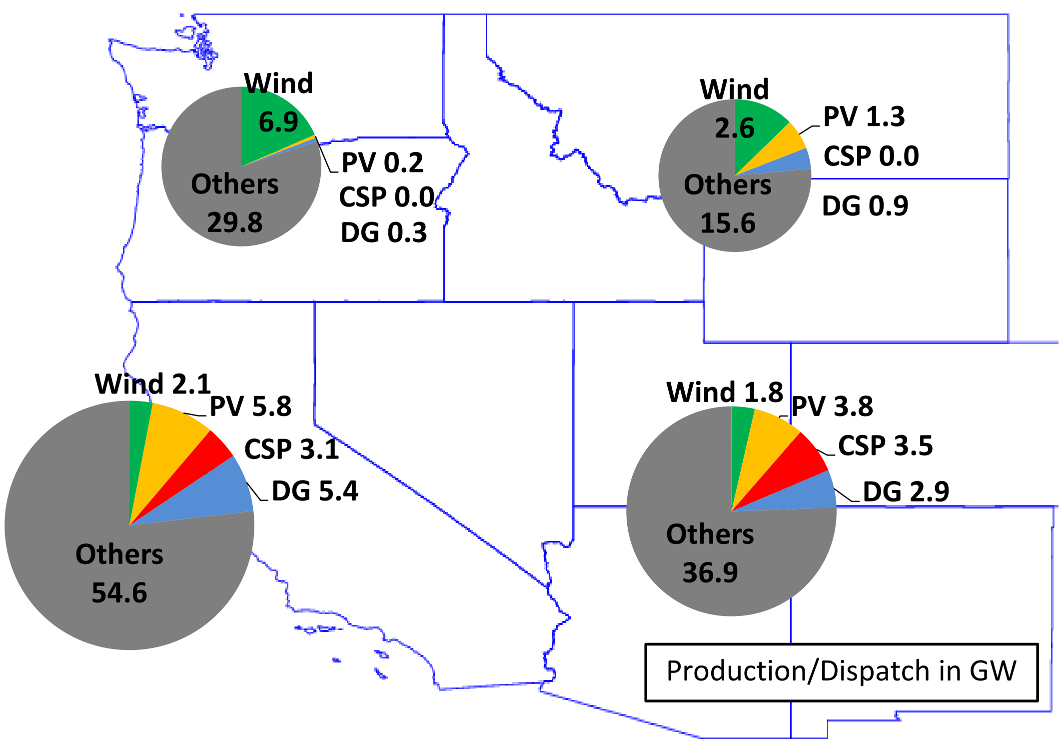

Figure 11. Wind and solar generation in the Heavy Summer Hi-Mix case.

Table 1. Renewable Generation Summary for All Study Scenarios

WECC-Wide Summary	Light Spring Base	Light Spring Hi-Mix	Light Spring Extreme	Heavy Summer Base	Heavy Summer Hi-Mix
Wind (GW)	20.9	27.2	32.6	5.6	14.3
Utility-Scale PV (GW)	3.9	10.2	13.5	1.2	11.2
CSP (GW)	0.9	8.4	8.3	0.4	6.6
Distributed PV (GW)	0	7.0	10.4	0.0	9.4
Total =	25.7	52.8	64.8	7.2	41.5
Penetration(1) (%) =	21%	44%	53%	4%	20%

(1) Penetration is % of total generation.

Frequency Response Results

As previously described, FR is the overall response of the power system to large, sudden mismatches between generation and load. The primary concern is that the minimum frequency, or nadir, during design-basis disturbances should not cause under-frequency load shedding (UFLS). In the West, the first stage of UFLS is normally at 59.5 Hz. The NERC standard also provides a specific definition of the quantitative metric “frequency response.” It is this metric that is compared to the frequency response obligation (FRO) to determine compliance.

This investigation focused on light spring conditions, as the relatively low level of generation may present a challenge for FR. Similarly, the analysis focused on the single largest design-basis generation outage in the Western Interconnection. According to BAL-003-1, this design-basis event is the trip of two fully loaded Palo Verde nuclear power station units for a loss of about 2,750 MW. The subsequent frequency excursion is severe, as shown in Figure 12. This frequency is an MVA weighted average of all WECC synchronous machine speeds. The frequency nadir is 59.67 Hz in the base case (blue line), 59.65 Hz for the high renewable case (green line), and 59.61 Hz for the extremely high renewable case (red line). Thus, all cases avoid UFLS relay action, which begins at 59.5 Hz.

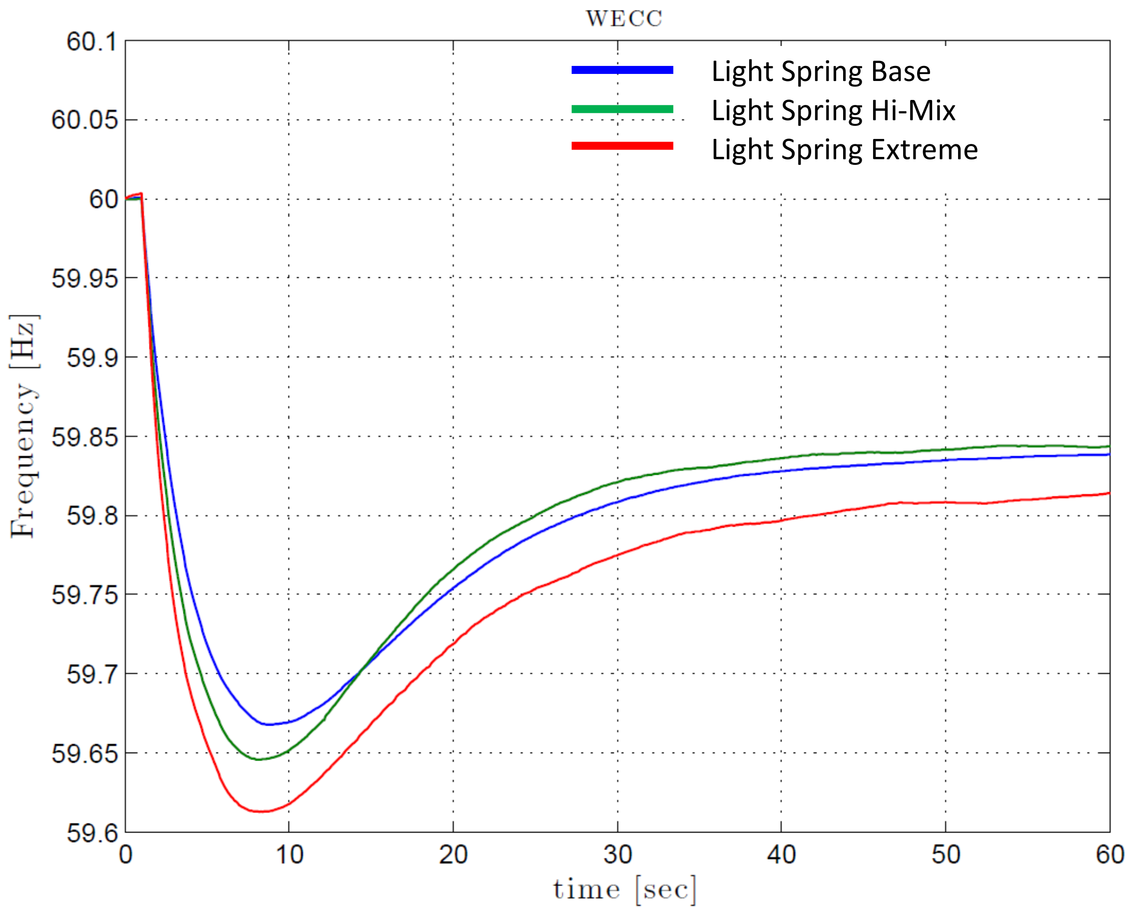

Figure 12. Frequency response to loss of two Palo Verde units under light spring system conditions.

The Western Interconnection frequency response obligation (IFRO) will be updated annually, according to the NERC BAL-003-1 standard. The IFRO is given as 840 MW/0.1 Hz for this study. To help understand the system frequency performance, estimates of regional FROs were made. These estimated FROs are listed in the first column of Table 2. Actual FROs are assigned to individual balancing authorities (BAs) and are updated annually, so these estimated obligations are for reference only. They should not be used to determine individual BA compliance with the NERC standard. Table 2 is a summary of the FR for WECC, and four large U.S. regions, for all the key cases.

The FR for cases plotted in Figure 3 are reported in their respective columns (Base, Hi-Mix and Extreme Hi-Mix). The WECC-wide FR meets its obligation in all cases, with some margin. Portions of the system that rely primarily on thermal generation tend to be short of meeting their approximate FRO with their own generation resources, especially in the Hi-Mix case (e.g., the Desert Southwest and Northeast regions). This occurs because that thermal generation was displaced by wind and solar, which do not provide FR unless equipped with specific controls. Other regions, particularly the Northwest, far exceed their approximate FRO due to high levels of responsive hydropower.

The other results shown in this table are from cases used to evaluate the impact of various means of improving FR. Three combinations of GE-standard frequency controls on wind plants were tested: governor control alone, inertial control alone, and the combination of the two. The inertial control alone has little impact on the FR metric compared to the Hi-Mix case. This control targets the first 10 seconds after a generation outage, while the FR metric is measured from 20 seconds to 52 seconds. One aggressive, non-standard control was used to test on the utility-scale PV. Note that the various combinations of frequency controls were only applied to the new wind plants and new utility-scale PV plants. In other words, only the wind and solar plants added to the Base case to create the Hi-Mix case, which are a subset of the total number of wind and solar plants, were used in these sensitivities. By contrast, the energy storage was sized specifically to provide the incremental FR needed for each area to meet its approximate FRO with its own resources. All the governor controls, regardless of technology, improved FR in the four regions.

Table 2. Summary of Frequency Response

		Light Spring Frequency Response (MW/0.1Hz)							
	FRO	**Base**	**Hi-Mix**	**Wind Governor Control**	**Wind Inertial Control**	**Wind Governor and Inertial Controls**	**Utility-Scale PV Governor Control**	**Energy Storage with Governor Control**	**Extreme Hi-Mix**
WECC	840	1,352	1,311	1,610	1,323	1,571	2,065	1,513	1,055
By Region									
CALIFORNIA	296	305	312	335	315	334	562	369	295
DESERT SOUTHWEST	220	215	119	240	111	215	475	224	97
NORTHEAST	82	61	47	140	40	129	135	85	51
NORTHWEST	131	434	483	528	507	528	537	487	280

A summary of the frequency nadirs and settling frequencies for the Light Spring cases is shown in Table 3. All of the frequency-responsive control options improved both the frequency nadir and the settling frequency.

Table 3. Summary of Frequency Nadir and Settling Frequency for Light Spring Cases

	Light Spring WECC System Frequency Measures (Hz)							
	Base	**Hi-Mix**	**Wind Governor Control**	**Wind Inertial Control**	**Wind Governor and Inertial Controls**	**Utility-Scale PV Governor Control**	**Energy Storage with Governor Control**	**Extreme Hi-Mix**
Frequency Nadir	59.668	59.646	59.654	59.685	59.691	59.752	59.688	59.613
Settling Frequency	59.839	59.844	59.864	59.853	59.877	59.893	59.861	59.814

Extreme Generation Loss

The FR to an extreme event (i.e., loss of three Palo Verde units) compared to that of the design-basis event (i.e., loss of two Palo Verde units) is close to linear, and showed a slight degradation due to the larger-sized event and more governor controls saturating. This is reassuring from a robustness perspective, though a severe event will still cause UFLS-triggered interruptions, just as it does today.

While UFLS action is allowed for a severe event like this extreme generation tripping, cascading failure is not. One sensitivity case in which the embedded PV DG was pessimistically assumed to have aggressive under-frequency tripping resulted in an acute frequency depression and would have likely caused widespread outages.

Distributed vs. Central Station Generation Tripping

System performance in response to a large DG outage was compared to a large central station outage, as shown in Figure 13. The system frequency plot shows that the DG event results in a less severe frequency nadir and a better settling frequency. The difference is relatively small and is primarily due to two factors. First, the loss of locally generated power depresses the load voltage and causes the net load to drop. This load relief helps the system frequency. A second factor is that the tripped DG is less than the 2,750 MW of the Palo Verde event, due to voltage effects on the tripping logic in the composite load model. However, the post-disturbance voltages tend to be different, which can have substantial impact on load active power. This result tends to reinforce the conclusion that load voltage sensitivity is a more important consideration for FR than load frequency sensitivity. Broadly, the location of the generation tripping is not as important as the amount of generation that is tripped. The mechanisms for widespread DG tripping are complex, so it may be possible for more DG to trip than was used in this sensitivity case.

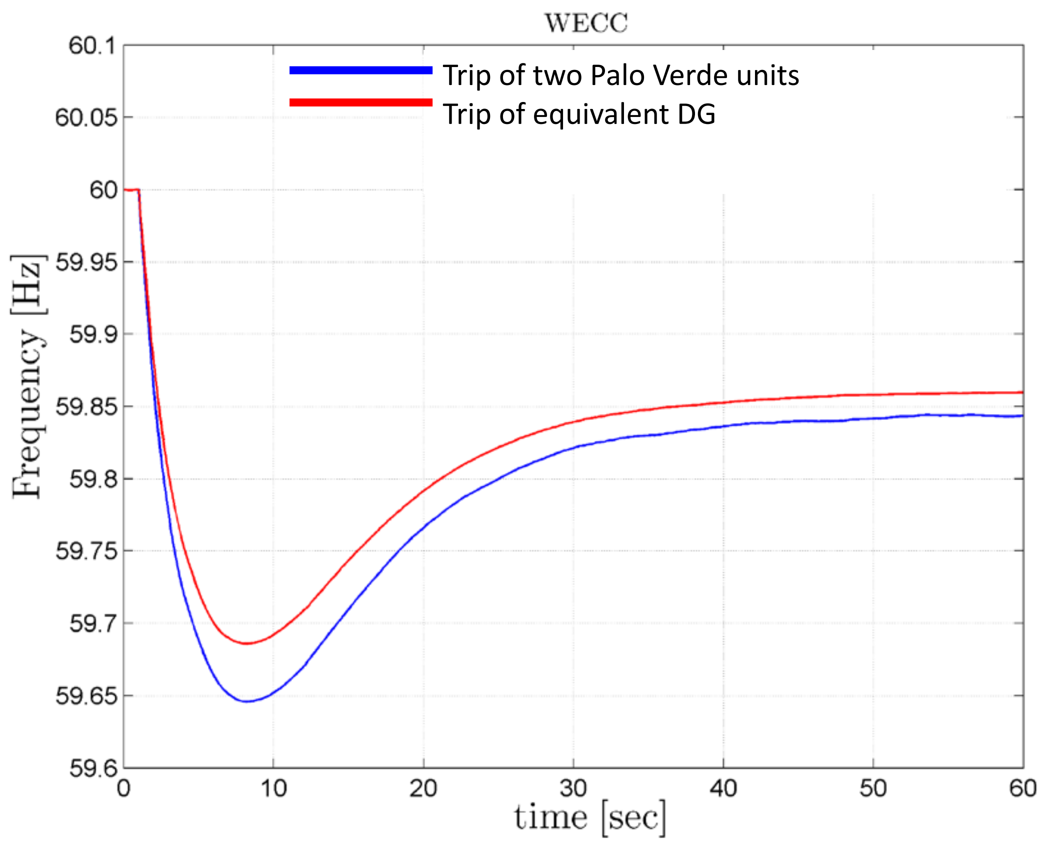

Figure 13. **Frequency response of Light Spring Hi-Mix case – DG trip vs. two Palo Verde unit trip.**

System Inertia

Much has been said about the possible impact of loss of system inertia due to the displacement of synchronous generation by inverter-based resources. Between the Light Spring Base case and the Hi-Mix case, the initial rate of change of frequency (ROCOF) increases about 18%. The impact of this increased ROCOF on the system stability is nearly invisible in terms of FR: both the nadir and the settling frequency are essentially unchanged. It should be noted that these levels of ROCOF, on the order of 0.1 Hz/s, are quite small compared to some of the smaller systems around the world that have ROCOF concerns primarily driven by the use of ROCOF relays. This reinforces other results that suggest that the loss of system inertia associated with increased wind and solar generation is of little consequence for up to at least 50% levels of instantaneous penetration for the Western Interconnection as long as adequately fast primary frequency responsive resources are maintained.

Headroom Depletion

The effects of headroom depletion due to a relatively rapid afternoon decline in solar PV generation—the so-called “duck curve”—is a growing concern. In an effort to bound the problem, an extreme case was simulated where all PV generation in the Western Interconnection was shut down, mimicking sunset, while no other generation was committed. This does not create a catastrophic failure in the system performance for the given commitment and dispatch. No dramatic changes in performance were observed (i.e., there was no cliff) as the PV dropped out. Rather, the degradation of FR is steady and monotonic, while transient stability was maintained.

However, once the PV output is reduced to zero, the overall WECC FR is marginal, even with significant contribution from California hydro. The FR for California is below the approximate statewide FRO. To test the impact of having less responsive hydro, governors were removed as a proxy for low water levels or other constraints on the hydro generators' ability to provide more power. As the California hydro becomes less responsive, the overall WECC FR drops, and eventually WECC fails to meet the IFRO.

As PV drops output, the system must be re-dispatched, which creates many local stress points (e.g., poor voltage and thermal overloads). This suggests that the need to commit/recommit units could be driven as much by local constraints as overall stability. The details will be important as the system stress builds. This further suggests that locational issues may drive some constraints on how system operators strive to maintain adequate FR.

Means to Improve Frequency Response

Current operating practice uses traditional approaches (e.g., commit conventional plants with governors) to meet all FR needs. Selected non-traditional frequency-responsive controls on wind, solar PV, CSP plants, and energy storage were examined in this study.

Frequency-Responsive Controls on Wind Plants

This study examined two types of frequency-responsive controls for wind plants. The Light Spring Hi-Mix case was tested with a governor function (or active power control), inertial control, and a combination of both. As shown in Figure 14, the inertial control helps improve the nadir, but the energy recovery tends to stretch out the frequency depression. A substantial improvement in the margin above UFLS is realized. Unlike the governor function, the inertial control has no opportunity or lost energy cost. There is, however, a capital cost associated with the controls.

The governor or active power control alone greatly improved the settling frequency and the frequency response, but had little impact on the nadir. The combination of both the governor and inertial control improved the frequency nadir, settling frequency, and frequency response. Note that the wind governor controls were set to emulate those on conventional generation. Both the wind governor and inertial controls could be made more aggressive, as is examined with the utility-scale PV and energy storage controls below.

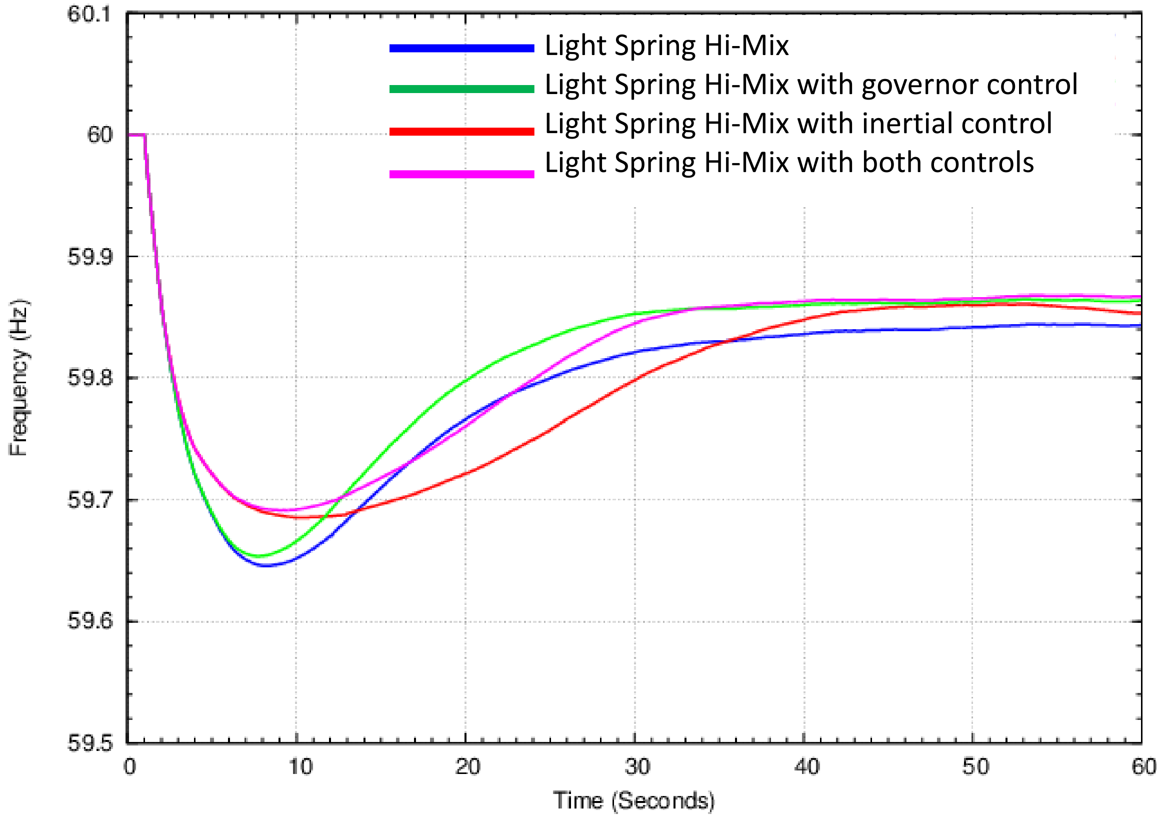

Figure 14. Frequency response to two Palo Verde unit trip for Light Spring Hi-Mix case with three combinations of frequency controls on wind plants.

Frequency-Responsive Controls on Utility-Scale Solar PV Plants

Primary FR from utility-scale solar PV generation is effective at improving both nadir and settling frequency, as shown in Figure 15. Unlike the governor controls for wind plants, the control used here is aggressive: the response is fast, with gains and time constants selected to saturate relatively quickly once the system frequency is outside of the dead band. The PV plant response to the design-basis event (i.e., loss of two Palo Verde units) is so fast that it is essentially a step response. Had the event been somewhat less severe, the control would still have saturated and provided a proportionally greater response. Thus, the FR metric would show a greater benefit. Conversely, had the event been even larger, the FR metric would be worse.

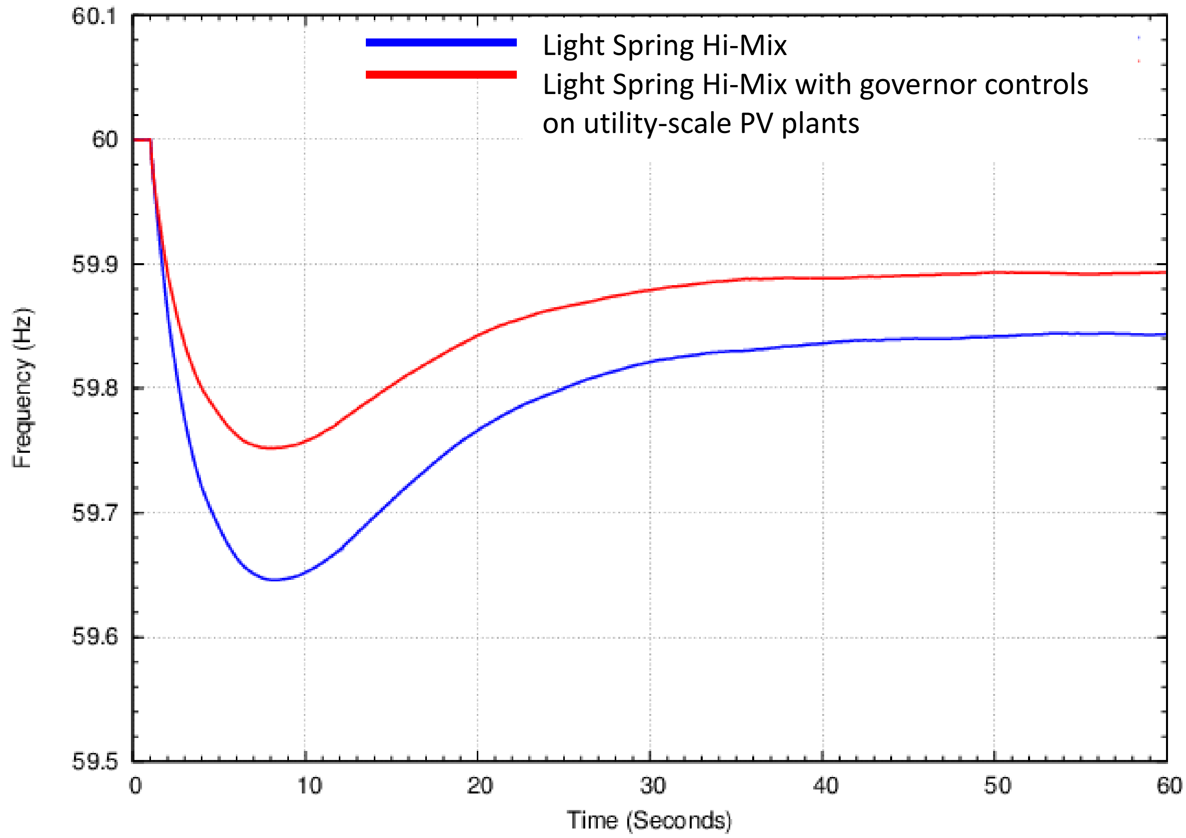

Figure 15. Frequency response to two Palo Verde unit trip for Light Spring Hi-Mix – with and without governor control on utility-scale PV plants.

Frequency Response from Energy Storage

This study shows that the WECC-wide FR meets NERC criteria and the system avoids UFLS for all cases examined. However, many of the individual areas are short of FR. Note that the FROs assigned to individual areas in this study are estimates. The NERC rules apply specifically and exclusively to individual BAs. There is no requirement that BAs meet their FROs with resources within their BAs.

In this investigation, inverter-based energy storage systems are added to areas short of FR. The model used for this investigation is deliberately independent of the storage medium (e.g., batteries, flywheels, super conducting magnetic energy storage, etc.). It is assumed that the medium has sufficient energy to supply the nominal power rating for 60 seconds and that it has the dynamic capability necessary to follow the change in power required for the control. The storage systems for each area were sized specifically to meet that area's estimated FRO, and an aggressive governor control was applied to each system. As shown in Figure 16, primary FR from fast energy storage is effective at improving both nadir and settling frequency. A total of about 400 MW of energy storage for all of the Western Interconnection allowed the individual areas that were short of FR to meet their approximate FROs with resources in their areas. The NERC requirements allow individual areas to contract with others for sufficient frequency-responsive resources to meet their obligation.

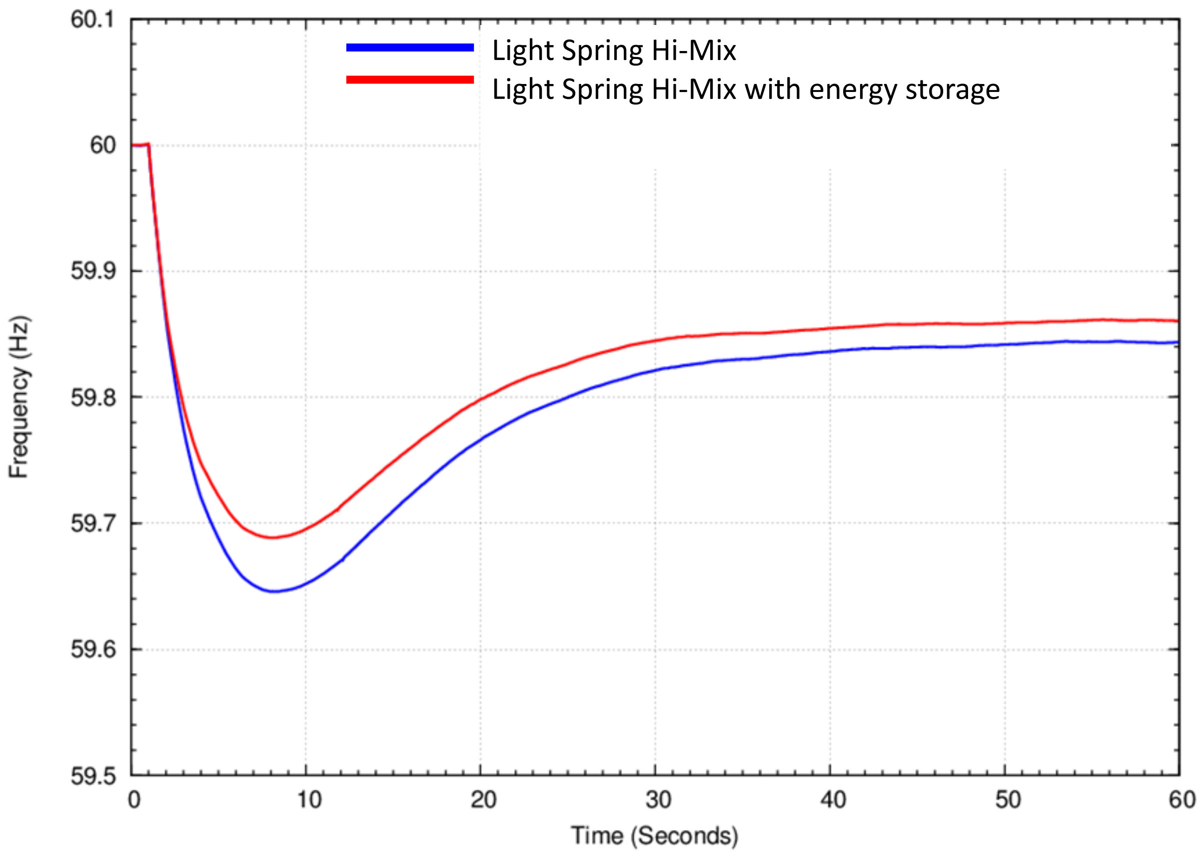

Figure 16. Frequency response to two Palo Verde unit trip for Light Spring Hi-Mix – with and without energy storage.

Transient Stability Results

During heavy load conditions, the addition of high levels of wind and solar generation increases the heavy loading on the Pacific AC and DC Interties to about their present path ratings. High flows on the California Oregon Interface (COI) are well known to be stressful and to require a generation-tripping remedial action scheme (RAS). The investigation suggests that this practice can continue, and that the transient stability of the system for one of the well-known and critical events for the Western Interconnection is not fundamentally changed by the high wind and solar generation, as shown in Figure 17. One sensitivity case in which the Base case had the same Pacific DC Intertie (PDCI) and COI loading had slightly worse performance than the Hi-Mix case. This conclusion is not a statement that the system behaves identically. It is possible, and perhaps likely, that the system dynamics are sufficiently different to require somewhat different levels of generator tripping or different arming criteria. A complete evaluation of the current practice to check for refinements would be prudent. There is, however, nothing in this analysis to indicate that the system dynamics have fundamentally changed and that radically different means to ensure stability for this event are required.

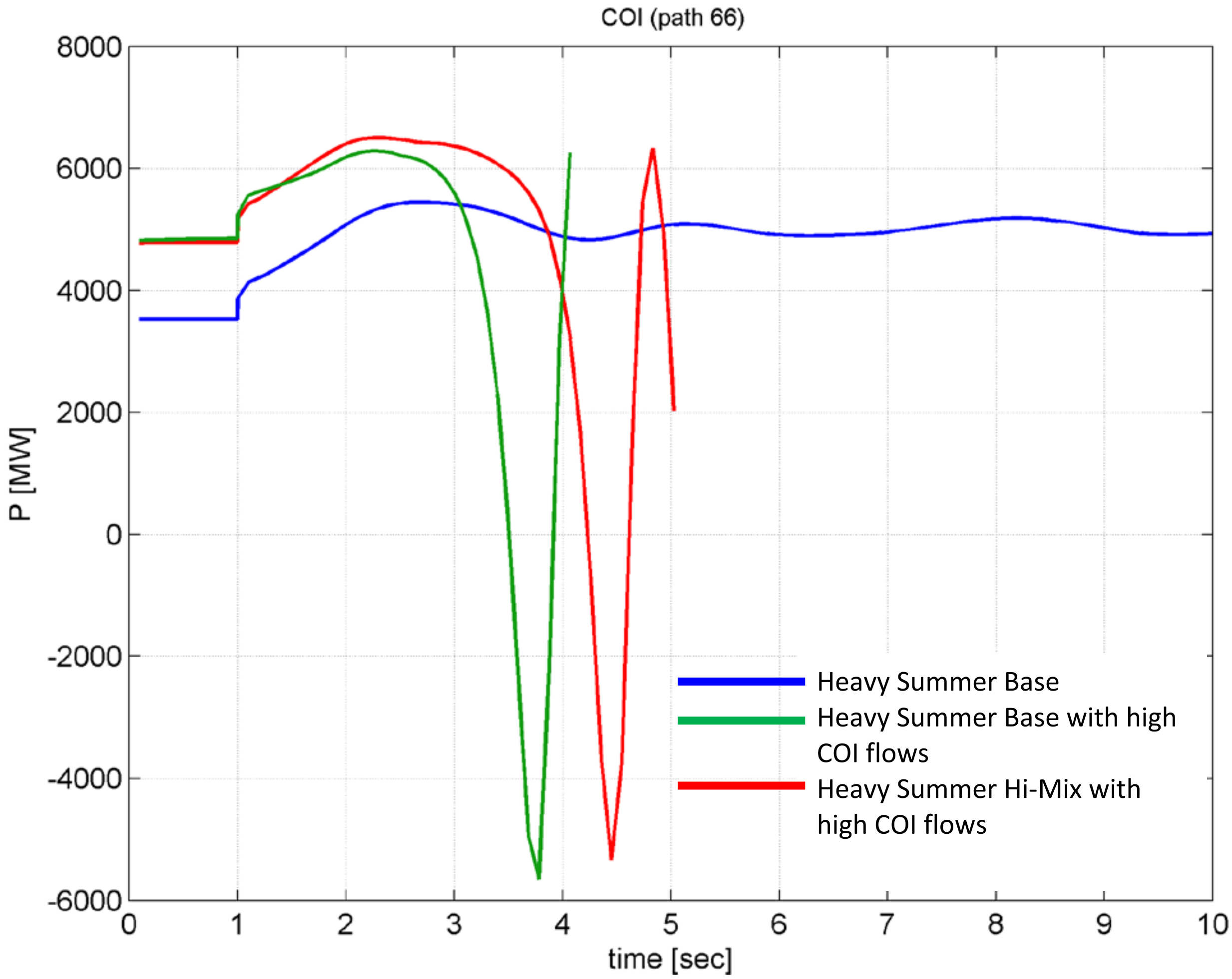

Figure 17. COI Flows for PDCI event for Heavy Summer cases.

Local Stability

There are many localized stability limits in the West. The addition of substantial wind and solar generation has the potential to alter the system dynamics of the events that dictate these limits.

For the limited examples, the local system stability is slightly better in the Hi-Mix case.

Distributed Generation Fault Ride-Through

The deliberate or sympathetic trip of distributed PV during disturbances results in a slower recovery and lower sustained voltages. Local reactive power balance can be disrupted, with reactive power demand increasing many times the amount of active power tripped. In one test, with a pessimistic approximation to a worst-case under-voltage tripping, the loss of the DG causes a system collapse.

A number of cases showed adverse consequences, up to and including system collapse, from widespread tripping of embedded PV DG. Consequently, both prudence and existing reliability rules would argue against widespread, common-mode DG tripping for moderately severe voltage dips or frequency excursions.

IEEE Standard 1547a, published in May 2014, revises three existing requirements for interconnection of DG with electric power systems. It now has significantly wider mandated ranges for DG allowable trip settings in response to utility abnormal voltages and frequency, with different specified settings allowed via mandatory mutual agreement between the power system and DG operators. However, when the grid experiences a large disturbance, if the IEEE 1547 default trip settings are used for all DG sites, then that may result in widespread DG tripping at the same time. The draft IEEE Standard 1547.8 further permits additional DG functions to support the grid, again via mutual agreement. Although this draft has initially been approved by IEEE balloters, it is undergoing final revisions before publication.

The system-wide impact of common-mode tripping of significant amounts of DG, regardless of the mechanism, requires more study.

Coal Displacement and Weak Grid in the Northeast Region

A high de-commitment of coal did not overstress the system, but local voltage and thermal problems did occur and were addressed with conventional transmission reinforcements. Figure 18 shows the change in dispatch with increasing wind and solar production in the Desert Southwest and Northeast regions for the Light Spring cases. A more than 80% reduction of coal commitment in the Northeast region in the Hi-Mix case, compared to the Base case, resulted in acceptable dynamic behavior for the limited tests performed. System dynamics were stable for an extra-high-voltage fault at Aeolus, in the heart of the high wind area of the Northeast. The system non-synchronous penetration (SNSP) was driven to 56% in the Hi-Mix case.

The regional transmission system was designed based on the size and location of the large coal power plants, which thus became critical nodes in the network. As a result, the transmission system operators have historically counted on those plants to provide the voltage and reactive power support needed for reliable operation. Displacement of those central plants by more dispersed wind and solar generation results in those nodes being poorly supported. Not surprisingly, local voltage and thermal problems occur, and good planning practices need to be followed.

The de-commitment in the Extreme sensitivity case further stresses the system, with a more than 90% reduction of coal commitment from the Light Spring Base case. This gives an SNSP of about 66%. The rapid voltage collapse and system separation during the fault, as shown by the green trace in Figure 19, is representative of so-called “weak grid” issues. Systems with very high levels of inverter-based generation are challenged to provide fast, confident control during faults and other disturbances. No commercially available wind or utility-scale solar PV generation is capable of operation in a system without the stabilizing benefit of synchronous machines. Therefore, the conversion of some coal plants to synchronous condensers and the addition of mechanically switched shunt compensation were needed to stabilize the Aeolus fault with the conservative load and wind plant modeling used. The synchronous condenser conversion (assuming retirement) works well to stabilize the system, as shown in Figure 19. The system recovers in an orderly fashion when the fault is cleared. The synchronous condenser conversion improves the SNSP from about 66% to 61%.

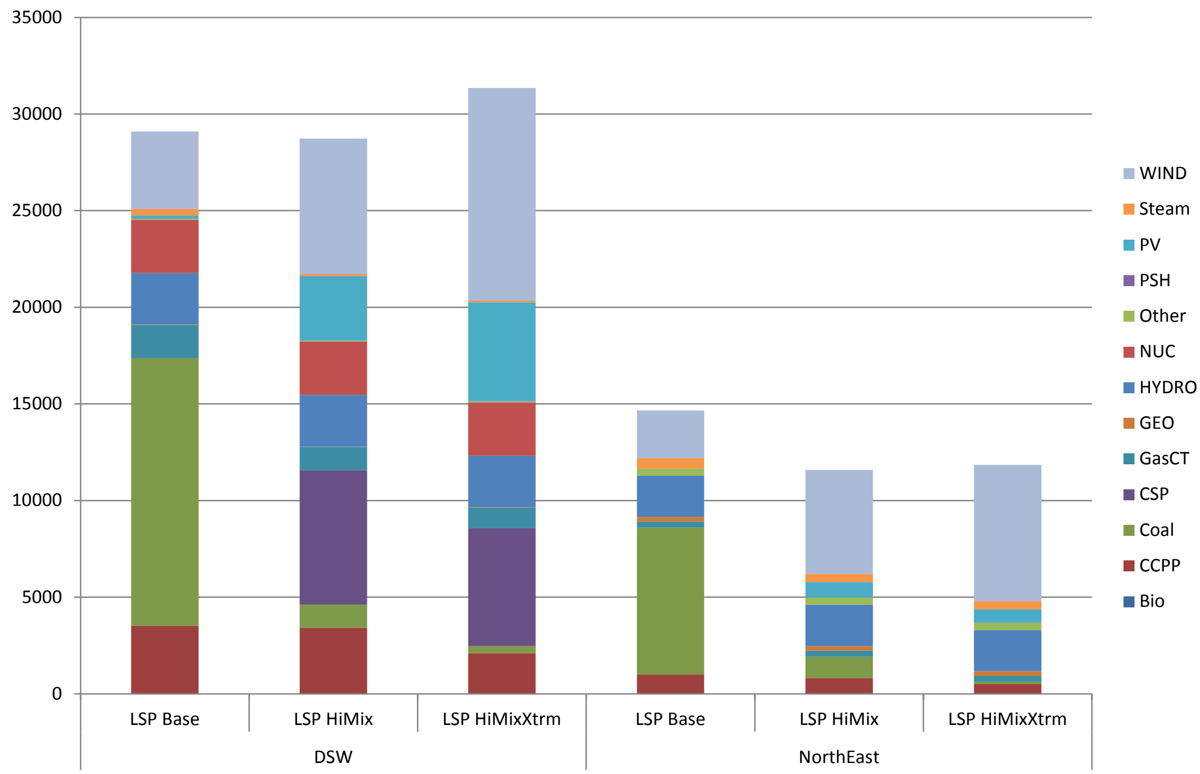

Figure 18. Coal displacement in Desert Southwest and Northeast regions for Light Spring cases.

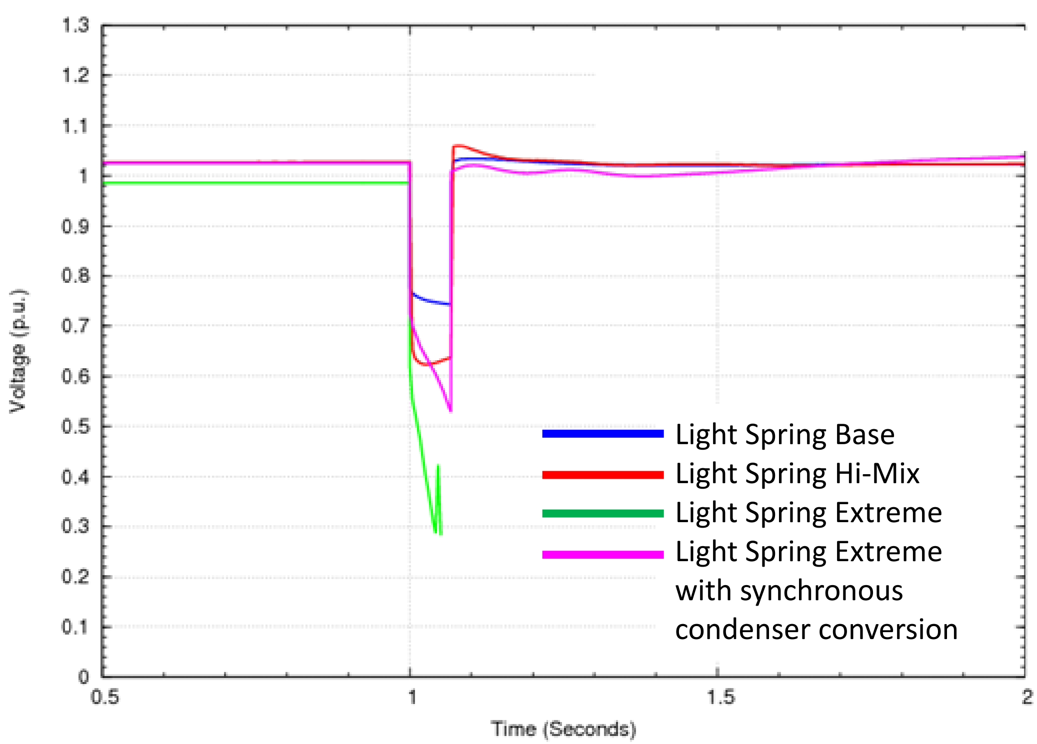

Figure 19. Dave Johnson bus voltage for Aeolus fault – Light Spring Base vs. Hi-Mix vs. Extreme vs. Extreme with synchronous condenser conversion.

Means to Improve Transient Stability

Transmission Additions

The mitigation investigation in WWSIS-3 included a portion of the WWSIS-2 transmission additions to examine their impact on the transient stability of the COI. The added transmission stabilizes the system without a generation-tripping RAS. This reinforces the need to analyze whether the interface limits should change.

Frequency-Responsive Controls on CSP Plants

The CSP plants are modeled as base load steam plants under most conditions. However, the potential contribution of CSP steam turbines to FR was examined by enabling GR on all the new CSP plants.

The PDCI event can cause system separation at the COI unless some RAS generation tripping is enabled. Figure 20 shows a potential benefit from having CSP GR. In this case, the PDCI event is imposed with the CSP GR enabled. The figure shows that the system is stabilized without resorting to a RAS. This is because the beneficial contribution of CSP is geographically advantageous for this event. Most of the CSP is to the south of the COI, so the transient increase in power output from these plants is such that power swing from north to south on the COI is slightly reduced and eliminates the voltage collapse along the corridor. Thus, the beneficial CSP contribution to FR also has a positive locational aspect that benefits transient stability.

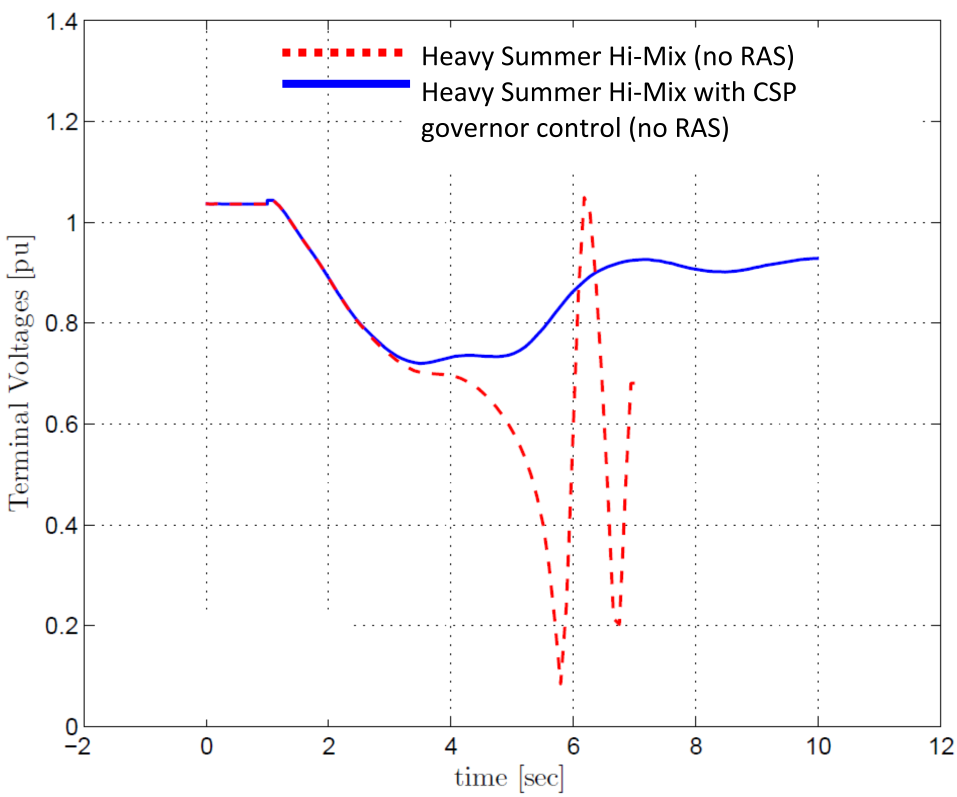

Figure 20. Malin station bus voltage in response to PDCI event – with and without CSP governor control.

Model Improvement and Further Analysis

Load Model

Changing the load model had a greater impact on system performance than did changing the level of renewable generation. The results of a three-phase fault at Vincent 500 kV in California for the Heavy Summer Original and Base cases are shown in Figure 21. The Original case uses the standard WECC load model, and the Base case uses the composite load model. The behavior of the system for deep faults is completely dominated by the load model, and more specifically by the tripping vs. stalling behavior assumed for the motor constituents of the composite load. The motor stalling behavior is exacerbated by blocking or tripping of embedded PV. This is an extraordinarily complex issue for planning and for research. This stability risk is not primarily one of utility-scale renewable integration.

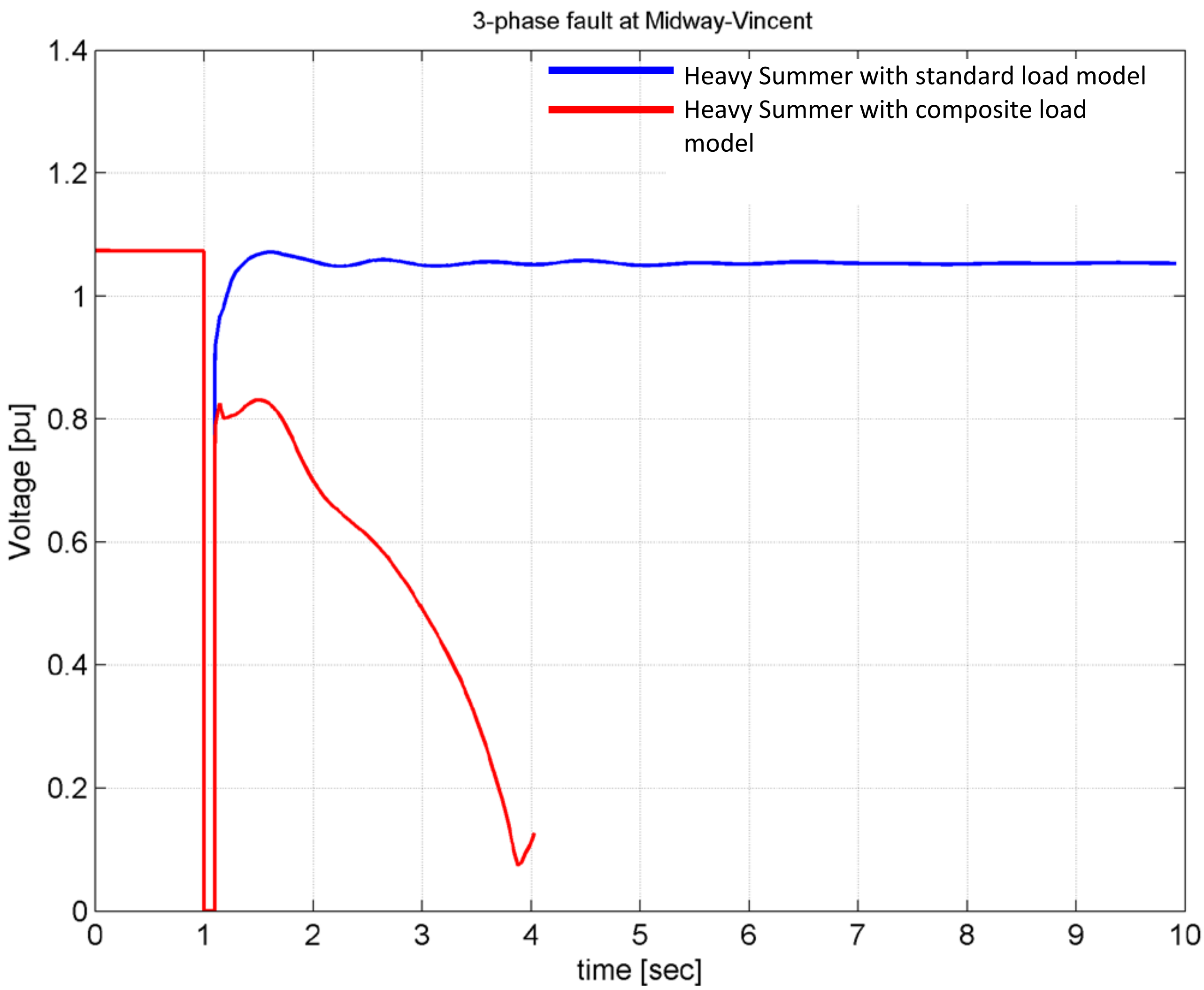

Figure 21. Load-induced voltage collapse in Heavy Summer Base case.

Wind and Solar Models

When wind and solar are the dominant source of generation throughout the region, it will be important to have appropriate dynamic models. WECC has a longstanding best practice to keep dynamic models up to date. Wind and solar plant models need to be held to the same level of accuracy in a high-penetration future. Adoption of wind plant controls designed for weak grids greatly improved system stability. Further, the results were extremely sensitive to the assumptions about load modeling, as described above.

Frequency-Responsive Control Philosophy

The combined findings of the wind, solar, and energy storage investigations suggest that the best use of rapidly responding power-electronics-enabled resources for FR is non-linear. The medium—wind or solar or energy storage or a combination—is less important than the control philosophy employed. Other technologies that deliver similar dynamic response, such as fast control of loads, would likely produce similar improvements.

In the past, the primary control variable was gain, in the form of governor droop, and speed of response was not readily adjusted. Coordinating droops and ensuring adequate response were more straightforward. With the added flexibility of easily adjustable speed of response, and the necessity to consider energy as well as power constraints, the frequency control problem also gains complexity. With the addition of non-linear frequency-responsive resources, practice will need to evolve and incorporate FR that is a function of the size of the disturbing event. As in the past, locational aspects may prove important in some cases.

Path Rating Analyses

The majority of the results presented in this study used the transmission topology directly from the WECC planning databases. These WECC cases included significant new transmission that is not currently in service. With the exception of some local patches, no further major reinforcements were added. In general, WWSIS-3 did not identify dramatic changes in system dynamics. However, the large changes in system flow patterns suggest that a rigorous analysis of individual paths is needed to ensure reliability. Certainly, all the regional paths in the high wind parts of the Northeast region will change as transmission is added to accommodate the new plants. A complete system evaluation is needed to assess the impact of a major transmission change like this on path limits.

Coal Displacement Analysis

The sequence of coal displacement sensitivities in this study is illuminating, but in no way complete or conclusive. It provides an opportunity to investigate the transient stability implications of not only temporary de-commitment of coal generation, but also the impact of possible coal plant retirements. The key point is that transient stability analysis is always based on snapshots of operation. From a system dynamics perspective, whether a specific generating resource is off-line because it was de-committed for a particular operating condition is indistinguishable from a permanent retirement. The displacement by wind and solar was based on the economic analysis of WWSIS-2 rather than an arbitrary, plant-by-plant choice.

The system appears to behave well for the Hi-Mix case when almost all the large coal plants in the eastern regions are off-line. However, displacing even more coal units and pushing SNSP above 60% appears to cause problems. This small sample suggests that care must be exercised in driving the system from a high level of coal displacement to an extreme level of coal displacement. More analysis is needed.

Conclusions

WWSIS-3 did not identify any fundamental reasons why the Western Interconnection cannot meet transient stability and FR objectives with high levels of wind and solar generation. However, good system planning and power system engineering practices must be followed. At a minimum, local voltage and thermal problems will inevitably require some transmission system improvements. The dynamic behavior of distributed PV generation was shown to have the potential to substantially impact the bulk power system. Distribution is not decoupled from transmission, and it will impact bulk power system operation. Mechanisms are needed to allow BAs to both share frequency-responsive resources and make sure that they have adequate frequency-responsive resources within their control. From a transient stability perspective, the system appears to tolerate substantial displacement of thermal generation. However, care will be needed in the event that the system, especially in the Desert Southwest and Northeast regions, is driven to near-zero commitment of coal plants. Note that this investigation is not a substitute for thorough system planning studies. The study conclusions are provided in bullet format below.

Transient Stability Conclusions

For the conditions studied:

- System-wide transient stability can be maintained with high levels of wind and solar generation if local stability, voltage, and thermal problems are addressed with traditional transmission system reinforcements (e.g., transformers, shunt capacitors, local lines). With these reinforcements, an 80% reduction in coal plant commitment, which drove SNSP to 56%, resulted in acceptable transient stability performance.
- With further reinforcements, including non-standard items such as synchronous condenser conversions, a 90% reduction in coal plant commitment, which drove SNSP to 61%, resulted in acceptable transient stability performance.
- Additional transmission and CSP generation with frequency-responsive controls are effective at improving transient stability.

Frequency Response Conclusions

For the conditions studied:

- System-wide FR can be maintained with high levels of wind and solar generation if local stability, voltage, and thermal problems are addressed with traditional transmission system reinforcements (e.g., transformers, shunt capacitors, local lines).
- Limited application of non-traditional frequency-responsive controls on wind, solar PV, CSP plants, and energy storage are effective at improving both frequency nadir and settling frequency, and thus FR. Refinements to these controls would further improve performance.

- Individual BA FR may not meet its obligation without additional FR from resources both inside and outside the particular area. As noted above, non-traditional approaches are effective at improving FR. Current operating practice uses more traditional approaches (e.g., committing conventional plants with governors) to meet all FR needs.

- Using new, fast-responding resource technologies (e.g., inverter-based controls) to ensure adequate FR adds complexity, but also flexibility, with high levels of wind and solar generation. Control philosophy will need to evolve to take full advantage of easily adjustable speed of response, with additional consideration of the location and size of the generation trip.

- For California, adequate FR was maintained during acute depletion of headroom from afternoon drop in solar production, assuming the ability of California hydro to provide FR.

Other Conclusions

- Accurate modeling of solar PV, CSP, wind, and load behavior is extremely important when analyzing high-stress conditions, as all of these models had an impact on system performance.
- Attention to detail is important. Local and locational issues may drive constraints on both FR and transient stability.
- The location of generation tripping, e.g., DG vs. central station, is not as important as the amount of generation that is tripped. However, widespread deliberate or common-mode DG tripping after a large disturbance has an adverse impact on system performance. It is recommended that practice adapt to take advantage of new provisions in IEEE 1547 that allow for voltage and frequency ride-through of DG to improve system stability.
- Further analysis is needed to determine operational limits with low levels of synchronous generation in order to identify changes to path ratings and associated remedial action schemes, as well as quantify the impact of DG on transmission system performance.
- Because a broad range of both conventional and non-standard operation and control options improved system performance, further investigation of the most economic and effective alternatives is warranted. This should include consideration of the costs and benefits of constraining commitment and dispatch to reserve FR, as well as the capital and operating costs of new controls and equipment.

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