Avangrid Renewables Tule Wind Farm

Demonstration of Capability to Provide Essential Grid Services

California ISO

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2. List of Acronyms

ACE	area control error
AGC	automatic generation control
APC	active power control
AWEA	American Wind Energy Association
BAAL	Balancing Authority Area Control Error Limit
CAISO	California Independent System Operator
CPS	control performance standard
FERC	Federal Energy Regulatory Commission
GE	General Electric
LGIA	Large Generator Interconnection Agreement
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
PFR	primary frequency response
POI	point of interconnection
PPC	power plant controller
ROCOF	rate of change of frequency
PV	photovoltaic
RPS	renewable portfolio standard
SCADA	supervisory control and data acquisition
SGIA	Small Generator Interconnection Agreement
UFLS	under frequency load shedding
WPP	wind power plant
WTG	wind turbine generator

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1. Abstract

The California Independent System Operator (CAISO), Avangrid Renewables, National Renewable Energy Laboratory, and General Electric (GE) conducted several tests to demonstrate that a large utility-scale wind power plant (WPP) can provide important ancillary services to the electric grid. The objective is to incentivize increased integration of renewable generation, which support not only the State of California's carbon reduction goals but also international efforts to decarbonize the electric power industry.

The results demonstrate that wind resources have the capabilities to help accelerate the shift toward a future electric grid with high levels of renewable generation. These results—much like those from a similar test in 2018 on an inverter-controlled solar power plant—promise next-generation advances for increased amounts of renewable generation, including pairing it with storage to create more effective dispatchable resources.

During several days in 2019, the team conducted a series of tests at Avangrid Renewables' Tule Wind Farm, located in CAISO's balancing authority in the McCain Valley, east of San Diego. The plant currently has a maximum capacity of 131.1 MW and participates in CAISO's energy market.

The various tests were designed to determine whether a WPP with an advanced plant-level controller with unique operating characteristics can enhance system reliability by providing essential reliability services to:

- Ramp up/down at specified ramp rates
- Respond to 4-second control signals from CAISO's energy management system
- Control scheduled voltage when the plant's output varies from zero to full output
- Provide fast frequency control within the inertia response time frame
- Provide frequency regulation similar to the governor actions of a conventional resource on governor control
- Respond to frequency response deviations for low- as well as high-frequency events.

The results show that a commercial WPP with an inverter-based smart controller can provide balancing or regulation up and down, voltage regulation control, active power control through ramping capability, and frequency response.

Currently, most renewable generation is built to fulfill a renewable portfolio standard (RPS) and is incentivized to maximize energy production. However, providing critical grid services might require renewable resources to operate below their maximum capabilities. Policymakers should consider alignment of RPS policies with RPS-driven renewables incentives to provide essential reliability services to the grid and help integrate increased levels of renewable generation.

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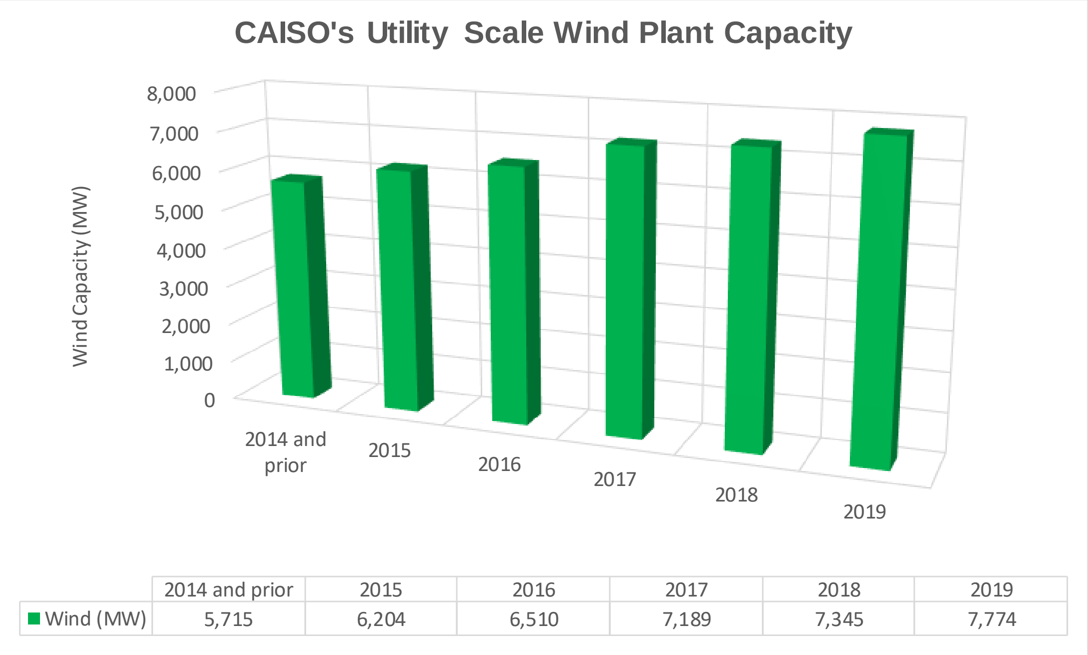
4. Introduction

During the past decade, the United States experienced unprecedented growth in new wind generation, which more than tripled in total installed capacity. Today, wind energy is the largest source of renewable generating capacity in the country. The U.S. wind industry reached a major milestone in September 2019 with a total wind operating capacity of more than 100 GW. There are now approximately 105.6 GW of wind generating capacity operating in 41 states and Guam and Puerto Rico.[1] In 2020, wind energy is expected to be the nation's primary source of renewable energy, surpassing hydroelectricity.

Wind power has many advantages: It is not dependent on a finite fuel source, it is low cost, it uses little water, and it does not generate substantial waste. These attributes contribute to its overall positive role in fighting climate change, promoting health benefits, and creating jobs. It also has some drawbacks, however: Wind generation is weather dependent; it has higher development and maintenance costs than some other renewable generation resources; and it has the potential to obstruct views, generate noise, and adversely impact wildlife [1].

The California Independent System Operator (CAISO) currently has approximately 7,774 MW of transmission-connected wind resources, including those located within its territory as well as those located outside that are contracted to load-serving entities within CAISO. To meet the State of California's renewable portfolio standard (RPS) goal of 60% renewable generation by 2030, CAISO is expecting to integrate approximately 3,000 MW of additional grid-connected wind capacity and 12,000 MW of additional grid-connected solar capacity [2].



	2014 and prior	2015	2016	2017	2018	2019
🟩 Wind (MW)	5,715	6,204	6,510	7,189	7,345	7,774

Figure 1. CAISO build-out of wind power plants

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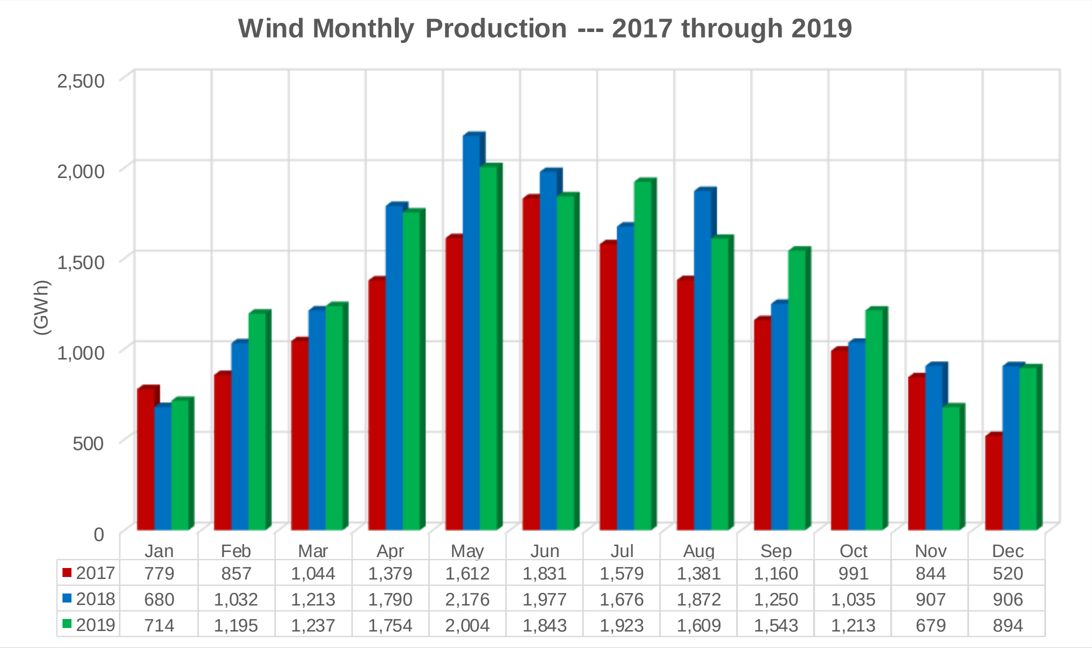
[1] American Wind Energy Association (AWEA) 2019-Q4 Market Report

In 2017, 2018, and 2019, CAISO's wind power plants (WPPs) generated 14.0, TWh, 16.5 TWh, and 16.8 TWh of energy, respectively, which served approximately 6.0%, 7.3%, and 7.6% of load, respectively. As shown in Figure 2, the maximum wind production typically occurs in May, followed by June and April.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
🟥 2017	779	857	1,044	1,379	1,612	1,831	1,579	1,381	1,160	991	844	520
🟦 2018	680	1,032	1,213	1,790	2,176	1,977	1,676	1,872	1,250	1,035	907	906
🟩 2019	714	1,195	1,237	1,754	2,004	1,843	1,923	1,609	1,543	1,213	679	894

Figure 2. CAISO's actual monthly wind production for 2017 through 2019

Although wind capacity has been increasing, there is concern that CAISO could experience multiple days without sustained wind, when the aggregated wind production could be less than 50 MW for multiple 5-minute real-time dispatch market intervals.

The red dots shown in Figure 3 correspond to the wind production at the time of CAISO's peak demand each day. The figure clearly shows that maximum daily peak wind production can vary dramatically and does not coincide with daily peak demand. This could be a concern as increased levels of renewable generation are integrated into the existing resource mix. Thus, additional analyses are needed to determine the amount of storage and responsive load that would be required to maintain reliability.

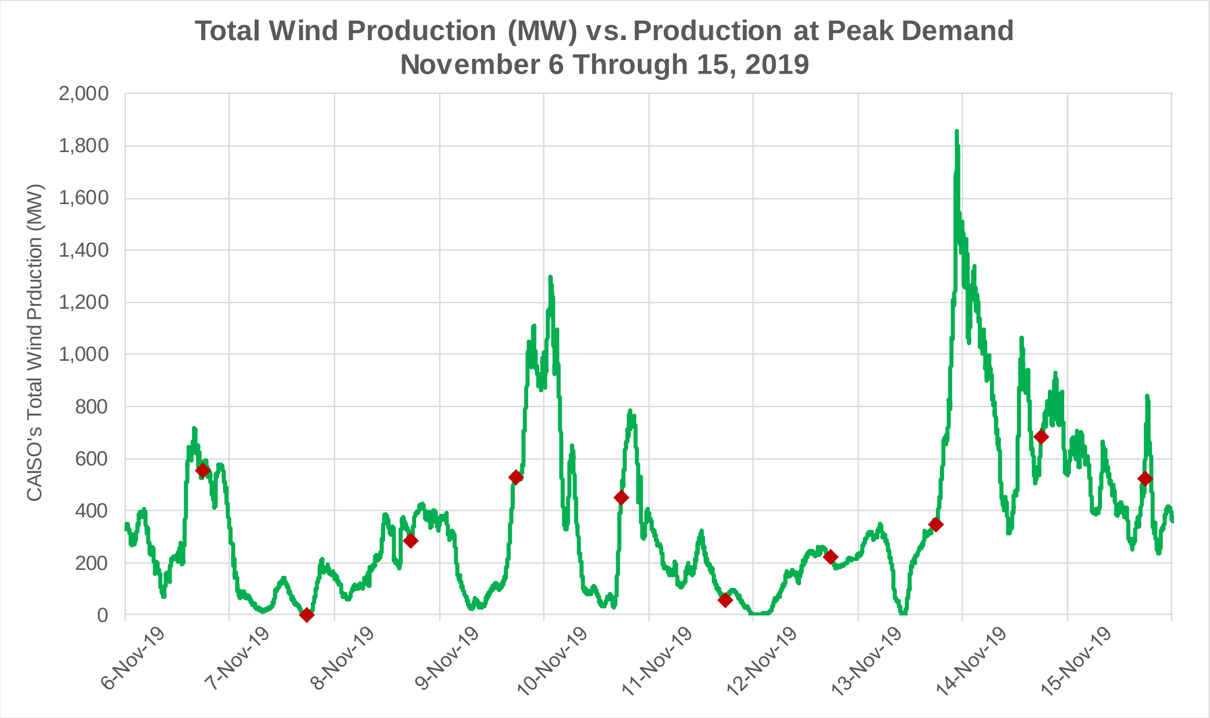


Figure 3. CAISO’s maximum daily wind production does not coincide with peak demand

As shown in Figure 4, wind production curtailment is more pronounced during the non-summer months and is expected to increase as more solar rooftop photovoltaic (PV) resources are added to the system, especially during high-hydropower years when demand is low and renewable energy production is high. At times of oversupply, wind resources could offer regulation-down service; and when curtailed for economic reasons, wind resources could offer regulation-up services. When wind production is curtailed, available headroom could be used to provide other essential grid services, such as frequency response for low-frequency events and ancillary services such as spinning and non-spinning reserves.

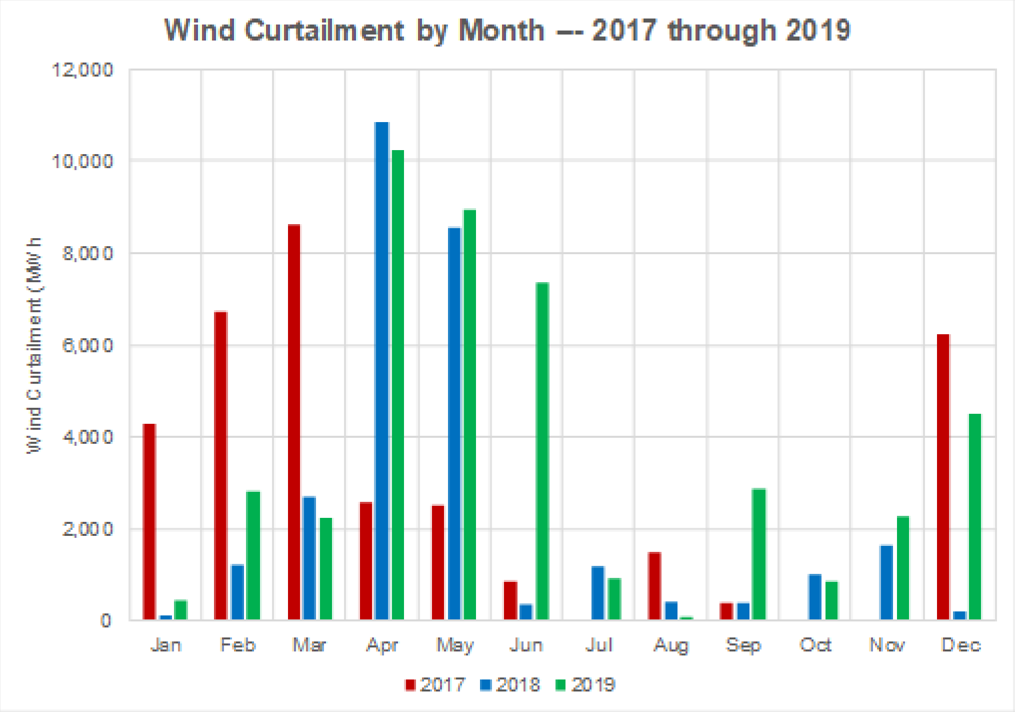


Figure 4. Aggregated monthly wind curtailment from 2017 through 2019

Figure 5 shows the installed wind capacity by state according to the American Wind Energy Association (AWEA) *U.S. Wind Industry Fourth Quarter 2019 Market Report*. Because of the rapid growth in variable renewable generation such as wind and solar in the United States and globally, power systems are undergoing a significant transition from those that are based on large, centralized power plants to more distributed systems. Integrating high levels of power converter–coupled variable renewable generation into an electric grid requires significant changes to electricity system planning and operations to ensure continued reliability; therefore, it is important to better understand how power converter–coupled renewable generation plants interact with the grid and how to use the advanced grid-friendly controls of renewables to maintain or enhance reliability.

Wind turbine generators (WTGs) are quite different from conventional steam, combustion, and hydropower turbines. Both the active and reactive power responses provided by wind resources are different from the responses from conventional power plants; therefore, it is essential that these responses be analyzed and understood to support power system reliability under high penetrations of wind. The results of this work can be used to improve existing designs as well as to provide input to new ancillary service market designs that allow wind to earn additional revenue and reduce overall costs to consumers. These services could increase the economic competitiveness of wind power, especially in coordination with other technologies, such as energy storage and responsive loads. The results of this work are also expected to benefit various stakeholders, including WTG vendors, WPP operators, utilities, transmission system operators, and reliability organizations.

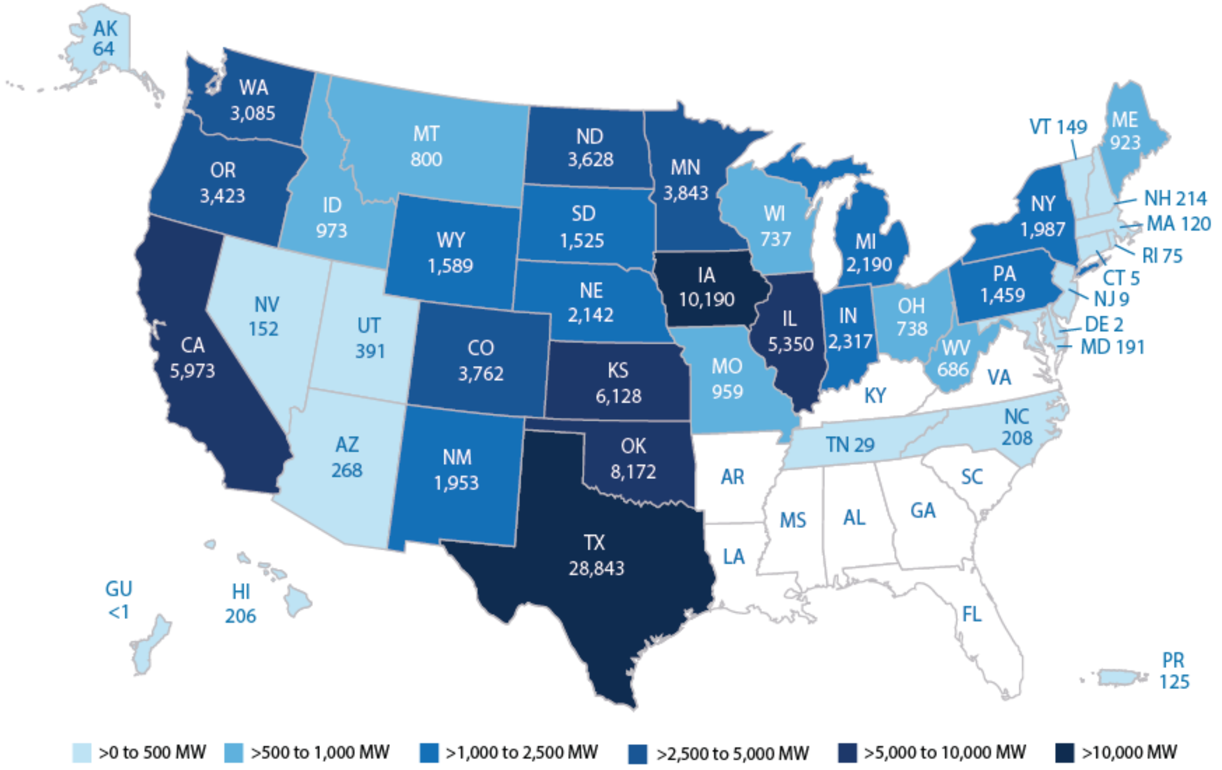


Figure 5. Operational wind capacity by state (Source: AWEA *U.S. Wind Industry Fourth Quarter 2019 Market Report*)

As shown in Figure 6, within CAISO's footprint, during off-peak months in the middle of the day when solar production is high and system demand is low, the risk of oversupply increases, leading to significant curtailment of renewables. This trend is expected to increase, especially during weekends. An example of such an operating day occurred on Sunday, April 21, 2019, when approximately 5 GW of renewable generation (shown by the red shaded area) needed to be curtailed to maintain reliable operation of the system.

Depending on the operating day, CAISO's non-dispatchable resources—such as nuclear, geothermal biomass/biogas, run-of-the-river hydropower, and some qualifying facilities—can vary between 5,000 MW and 7,000 MW, which can contribute to oversupply conditions and a lack of flexibility on the system. Figure 6 also shows the need for flexible renewable resources to help maintain system reliability.

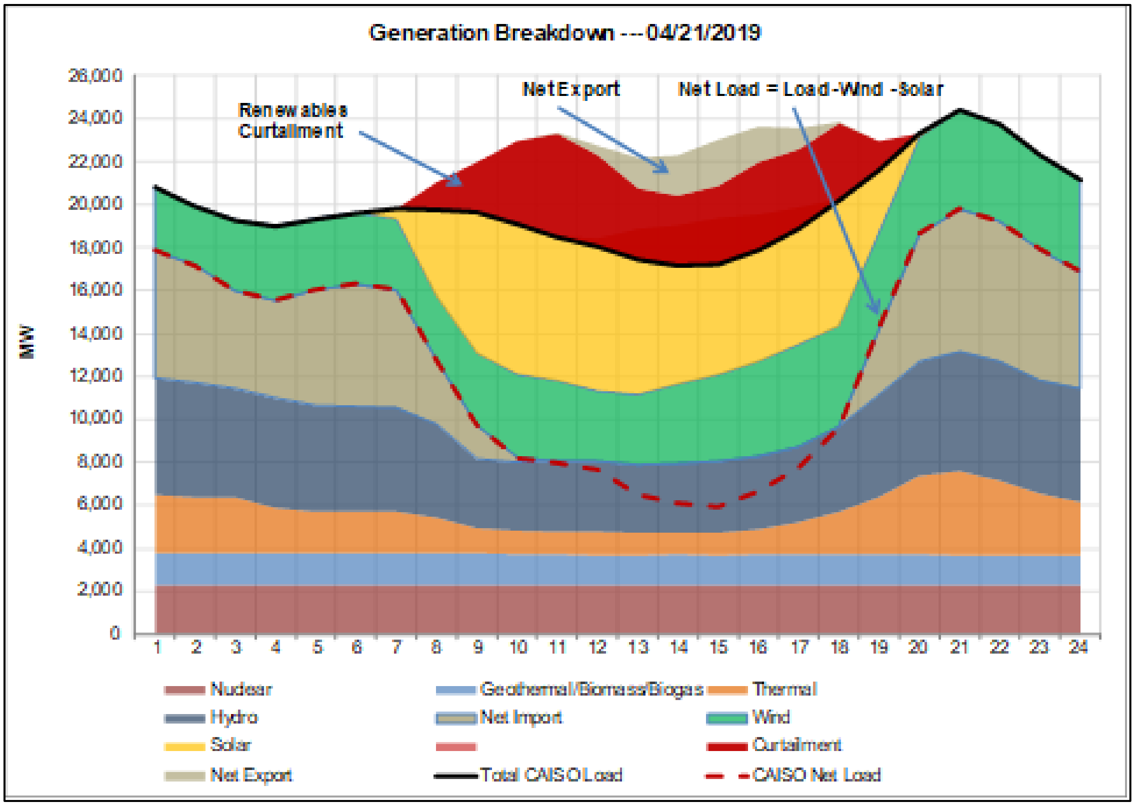


Figure 6. CAISO generation breakdown for April 24, 2019 (Source: CAISO)

It is expected that as more renewable resources are integrated into CAISO's resource mix, more opportunities will be created for controllable renewable resources to provide essential reliability services, which would help reduce carbon emissions by replacing conventional resources that provide these services.

Advanced inverter functions, along with improved design and operation of WPPs, can mitigate grid operational challenges and reduce curtailment of renewable generation. Although renewable curtailment is increasing, note that total wind curtailment in 2019 was 43.6 GWh, which was only 0.27% of the total wind production, and total solar curtailment was 921.7 GWh, which was only 3.2% of total solar production.

A typical modern utility-scale WPP is a complex system of several hundred turbines and multiple power electronic inverters. These inverters can reduce the impacts on grid stability and reliability through sophisticated, automatic, grid-friendly controls. Many wind control capabilities demonstrated in this project have already been proven, to some extent, to be technically feasible, and a few areas in the United States and throughout the world have started to request or require some WPPs to provide some form of essential reliability services. In the United States, however, although utility-scale WPPs are recognized as having these capabilities, they are rarely used by utilities or system operators to provide essential grid services.

CAISO is continually adapting its operational practices and market mechanisms to make the integration of increased levels of renewable generation both reliable and economically viable.

The transition to more renewable energy resources on the grid leads to a growing need by CAISO and other independent system operators and regional transmission operator for:

- Better coordination between day-ahead and real-time markets
- Increased flexibility in the form of fast ramping capacity
- Better use of ancillary service capabilities by variable renewable generation
- Expanded regional coordination
- Implementation of new market mechanisms incentivizing the participation of renewable generation in ancillary service markets
- Development of new market products to take advantage of faster and higher precision ancillary service providers
- Addition of energy storage capacity
- Aligning time-of-use rates with system demand.

Currently, regulation up and regulation down are two of the four ancillary service products that CAISO procures through co-optimization with energy in the day-ahead and real-time markets. The other two products are spinning and non-spinning reserves. Most ancillary service capacity is procured in the day-ahead market; however, CAISO procures incremental ancillary services in the real-time market process to replace unavailable ancillary services or to meet additional ancillary service requirements.

Currently, only a few grid operators in the United States use renewable curtailment as a resource. For example, the Public Service Company of Colorado can control its wind generation to provide both up- and down-regulation services. The Public Service Company of Colorado can use wind reserves as an ancillary service for frequency regulation by integrating WPPs in their footprint to their automatic generation control (AGC) system. Similar services can be provided by curtailed wind and PV power plants in California; however, regulatory, market, and operational issues need to be resolved for this to become possible.

Prior to testing the Tule WPP, the team developed a plan that was coordinated with technical experts from General Electric (GE) and Avangrid Renewables (see Appendix). Test descriptions and results are presented in the next sections. The following tests were conducted:

a. Regulation up and down
b. Frequency response tests with 4% and 5% droop setting for over- and under-frequency conditions
c. Frequency response test at a plant deadband of 36 mHz and 16 mHz
d. Active power control (APC) tests to demonstrate that the plant can decrease or increase its output at specific ramp rates
e. Voltage and reactive power control tests close to 0 MW of active power or close to maximum megawatt capability.

5. Description of Avangrid Renewables' Tule Wind Farm

Tule is a 131.1-MW WPP located in the McCain Valley, east of San Diego, within CAISO's footprint. Figure 7 shows the plant. The plant is connected via a combination of underground and overhead distribution lines to a 150-MVA (138/34.5-kV) transformer. The 34.5-kV side of the transformer supplies four circuits. Three of these circuits connect to supply turbine circuits via (34.5-kV/690-V) pad-mounted transformers that connect directly to individual turbine converter units rated at 4 MVA. The fourth circuit is connected to three switched capacitor banks rated at 21 MVAR to meet the Large Generator Interconnection Agreement (LGIA) power factor requirements. This is explained in more detail in Section 8.

Figure 7. Tule 131.1-MW wind farm (Source: Avangrid Renewables)

A key component of the Tule WPP is the power plant controller (PPC) developed by GE. It is designed to regulate real and reactive power output from the WPP so that it behaves as a single large generator.

GE's PPC can provide the following plant-level control functions:

- Dynamic voltage and/or power factor regulation and closed-loop voltage control of the WPP at the point of interconnection (POI) or the high side of the generator step-up transformer
- Real power output curtailment of the WPP when required so that it does not exceed an operator-specified limit
- Ramp-rate controls to ensure that the WPP output does not ramp up or down faster than a specified ramp-rate limit
- Frequency control (governor-type response) to reduce plant output in case of an over-frequency situation or increase plant output, if possible, in case of an under-frequency situation
- Fast startup and shutdown control when the wind is available.

Although the plant comprises individual inverters, with each inverter performing its own energy production based on local wind speed, the function of the plant controller is to coordinate the power output to provide typical large power plant services, such as APC and voltage regulation, through reactive power regulation.

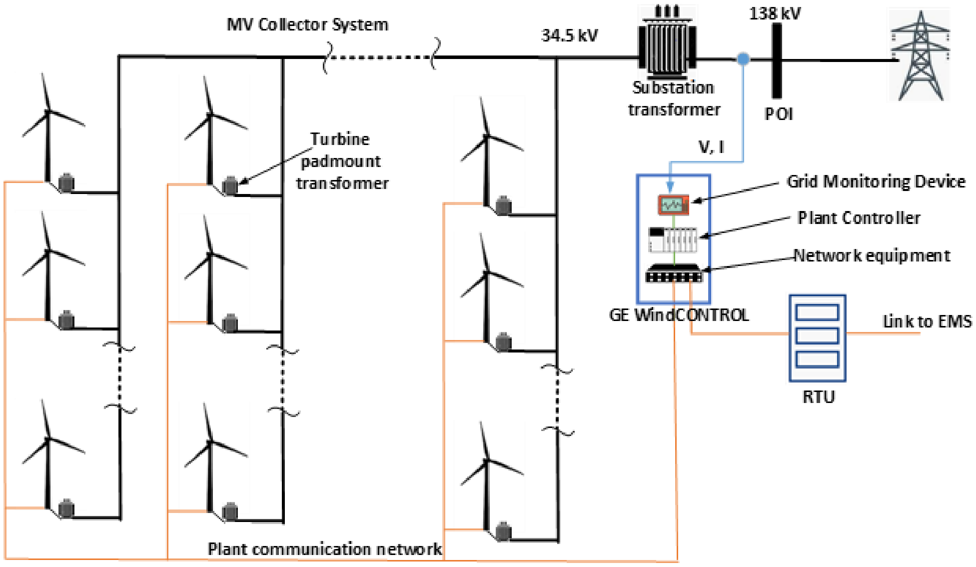


Figure 8. Modern WPP controls (Source: NREL)

GE's PPC implements plant-level logic and closed-loop control schemes with real-time commands to the inverters to achieve fast and reliable regulation. The PPC relies on the ability of the inverters to provide a rapid response to commands from the PPC.

Figure 8 illustrates a conceptual block diagram of the Tule WPP control system and its interfaces to other devices in the plant. The PPC monitors system-level measurements and determines the desired operating conditions of various plant devices to meet specified operating targets. It also manages the capacitor banks at the plant to maintain a scheduled voltage. It has the critical responsibility of managing all the inverters in the plant, continuously monitoring the conditions of the inverters and commanding them to ensure that they are producing the real and reactive power necessary to meet the desired voltage schedule at the high side of the generator step-up transformer bank.

The plant operator can set an active power curtailment command to the PPC, which calculates and distributes any active power curtailment to individual inverters. In general, some types of inverters can be throttled back only to a specified level of active power, causing the DC voltage at the plant to increase beyond its operating range. Therefore, the PPC dynamically stops and starts inverters as needed to manage the specified active power output limit. It also uses the active power management function to ensure that the plant output does not exceed the desired ramp rates, to the extent possible.

6. Automatic Generation Control Tests Conducted at the Tule Wind Farm

Typically, a modern wind turbine will start to generate electricity when wind speeds reach a cut-in speed at approximately 6 to 9 mph, and it will shut down at a cut-out speed if the wind speed exceeds roughly 55 mph to prevent equipment damage. Wind speed largely determines the amount of electricity generated by a wind turbine. Higher wind speeds generate more power because stronger winds cause the blades to rotate faster, which translates into more mechanical power and more electrical power from the wind turbines. The relationship between wind speed and power output for a typical wind turbine is shown in Figure 9.

Between the cut-in speed and the rated speed, where the maximum[2] output is reached, the power output will increase cubically with wind speed. For example, if wind speed doubles, the power output will increase eight times. This cubic relationship makes wind speed an important factor for wind power up to the rated wind speed. This leads to the relatively flat part of the blue curve shown in Figure 9.

The cut-in and cut-out speeds are related to the turbine design and size and are decided on prior to construction. The aggregate power output of a large WPP consisting of tens or hundreds of units is different from the power curve of a single WTG because of the increased diversity of wind speeds among the turbines. This is demonstrated in the notional graph shown in Figure 9, which compares the power curve of a typical utility-scale wind turbine with the theoretical aggregated power curve of a large WPP. (The x-axis is the weighted average wind speed throughout the whole plant.) As the plant size and the number of turbines at the plant increases, the aggregate power curve might differ more than that of a single turbine [3]. Also, WPPs can be curtailed to provide active power headroom for frequency response, spinning reserve, and up-regulation, as shown by the orange dashed curve.

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[2] The Betz limit is the theoretical maximum efficiency for a wind turbine, conjectured by German physicist Albert Betz in 1919. Betz concluded that this value is 59.3%, meaning that at most only 59.3% of the kinetic energy from wind can be used to spin the turbine and generate electricity. In reality, however, turbines cannot reach the Betz limit, and common efficiencies are in the range of 35%–45%.

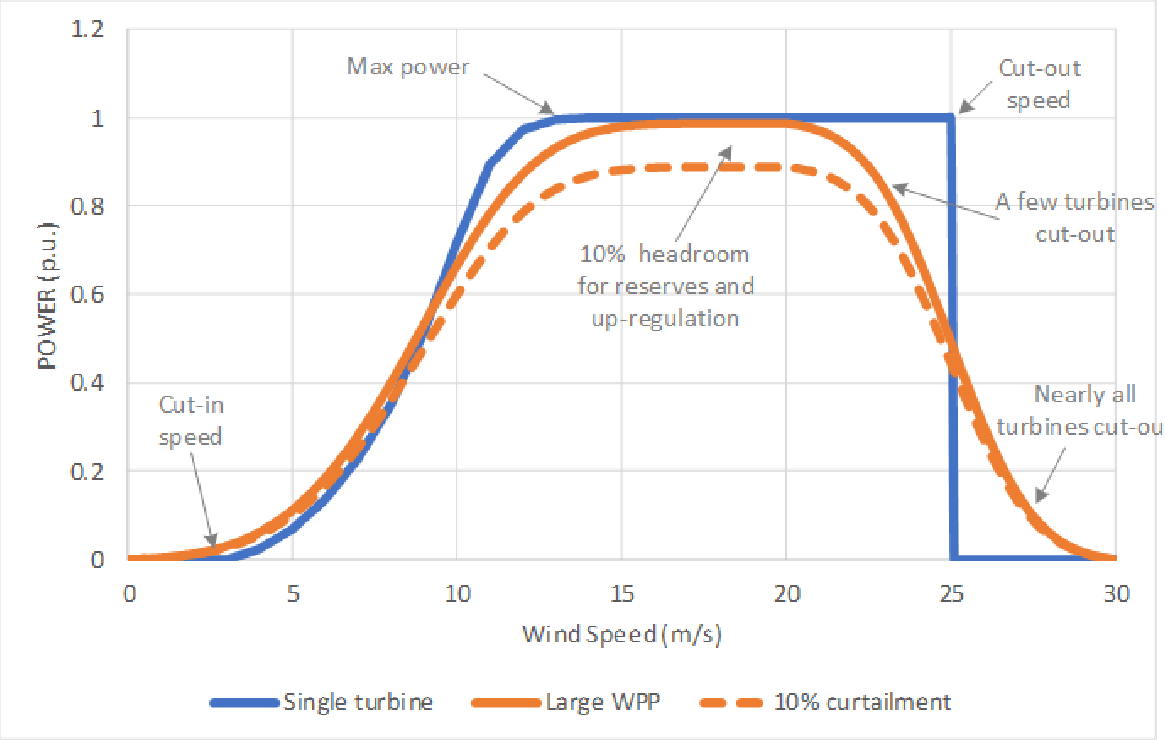

Figure 9. Wind generation power curve (Source: NREL)

6.1 Description and Rationale for Automatic Generation Control Tests

The purpose of the AGC tests is to demonstrate the capability of the WPP to follow active power set points sent by CAISO's energy management system to the plant. The set point signal is received by the remote terminal unit located in the plant substation and then scaled and routed to the PPC in the same time frame. When a plant is in AGC mode, the PPC initially sets the plant to operate at a power level (e.g., 20 MW) that is less than the estimated available peak power to have headroom for following an up-regulation AGC signal. See the hypothetical example shown in Figure 10.

The lower boundary of AGC operation can be set at any level less than available peak power, including full curtailment if necessary.

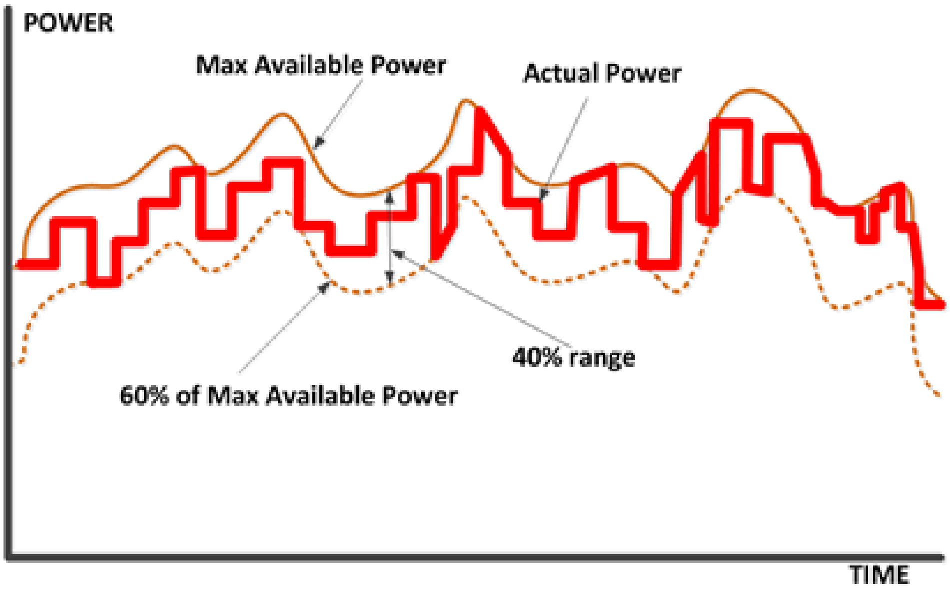

Figure 10. Concept of a resource following an AGC signal (e.g., with 10% headroom) (Source: NREL)

CAISO's AGC system is normally set to send a direct megawatt set point signal to all resources participating in regulation service every 4 seconds. The AGC control logic for a balancing authority with interconnections to neighboring balancing authorities (such as CIASO) is based on determining the:

- Balancing authority area's total desired generation
- Dispatch operating target for each AGC participating unit
- Regulation obligation for each AGC participating unit.

Area control error (ACE) is an important factor used in AGC control. For a balancing authority's area, ACE is determined as:

$$ACE = -\Delta P_{tie} - 10B(f_a - f_s) + I_{ME} + I_T \qquad (1)$$

where:

- ΔP_{tie} is the net tie-line interchange error
- B is the frequency bias (MW/0.1Hz)
- f_a and f_s are the actual measured and scheduled frequencies, typically 60-Hz
- I_{ME} is the tie-line meter error correction (MW)
- I_T is the time error correction factor (MW).

The ACE value used by the AGC control logic determines the total desired generation that will drive ACE to zero. The desired generation level of each generator participating in regulation service is split into two components: (1) a dispatched operating target (DOT), and (2) a desired regulation level. The dispatch operating target for each generating unit is set at its economic dispatch point through the real-time market, and the total system regulation needs are calculated as the difference between the total desired generation and the sum of the dispatch operating targets for all AGC participating units. The total regulation for the whole system is allocated among all participating regulating units. The WPP is considered as one plant-level resource (i.e., individual inverter outputs are not considered by CAISO's AGC system). Various unit-specific parameters are used in the regulation allocation, such as ramp rates and operating limits.

Figure 11 shows a conceptual diagram of CAISO's AGC distributing set point signals to individual generating units providing regulation service. The raw ACE signal is first filtered, and then it is processed by filters that have proportional and integral control gains. The filtered ACE is then passed to the AGC calculation and distribution module, which generates ramp-limited AGC set points for individual participating units based on their participation factor, dispatch status, available headroom, unit physical characteristics, etc.

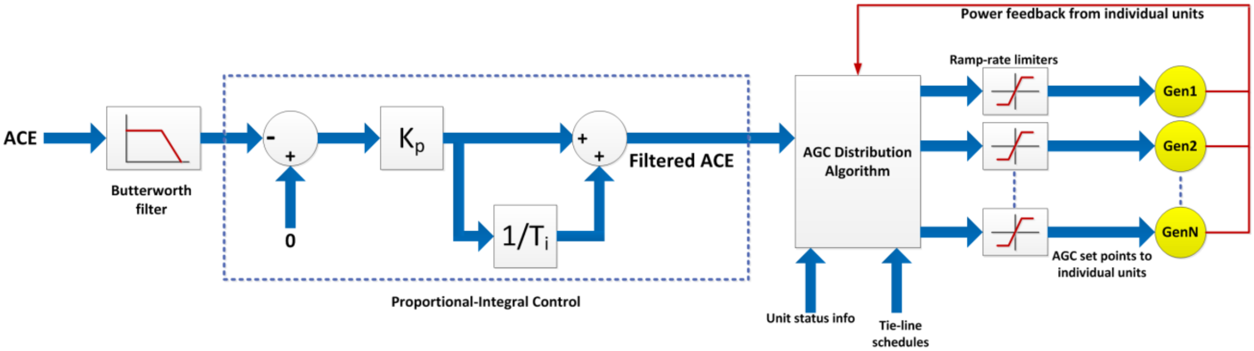

Figure 11. Simplified diagram of a typical AGC system (Source: NREL)

AGC operates in conjunction with supervisory control and data acquisition (SCADA) systems [4]. The SCADA systems gather information on system frequency, generator outputs, and actual interchange between a balancing authority and adjacent balancing authorities. Using system frequency and net actual interchange, with knowledge of net scheduled interchange, an AGC system determines the system's energy balancing needs in near real time [5]. CAISO's SCADA system polls sequentially for electric system data, with a periodicity of 4 seconds. The degree of success of the AGC in complying with balancing and frequency control is manifested in a balancing area's control performance compliance statistics and metrics, which are defined by the North American Electric Reliability Corporation (NERC) control performance standards (CPS). CPS1[3] is a measure of a balancing area's long-term frequency performance with the control objective to bound excursions of 1-minute average frequency errors during a 12-month rolling average. CPS1 evaluates how well a balancing area's ACE performs in conjunction with the frequency error of the whole interconnection.

The NREC's Standards Committee approved a new performance measure, Balancing Authority ACE Limit (BAAL), which is unique to each balancing authority and provides dynamic limits for its ACE value limits as a function of the interconnection frequency. The objective of BAAL is to maintain the interconnection frequency within predefined limits. Enforcement of BAAL began

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[3] CPS1 is a statistical measure of a balancing authority's ACE variability in combination with the interconnection frequency error from the scheduled frequency. NERC evaluates each balancing authority's ability to maintain its CPS1 score above 100% during a 12-month rolling average.

on July 1, 2016 [6]. Both CPS1 and BAAL scores are important metrics for understanding the impacts of variable renewable generation on system frequency performance. NERC reliability standards require that a balancing authority balances its resources and demand in real time so that the clock-minute average of its ACE does not exceed its BAAL for more than 30 consecutive clock-minutes.

6.2 Active Power Control and Automatic Generation Control Test Results

6.2.1 Active Power Control

A WPP needs to operate in a curtailed mode to provide enough reserves for various types of APC, including primary frequency response (PFR), participation in AGC, and spinning reserve. The reserve available (i.e., headroom) is the available power curtailed, which is shown as the area highlighted in yellow in Figure 12.

This APC test example shows how the aggregate plant output can be controlled in a curtailed mode to provide various types of active power responses depending on the requirements by a system operator. This could include operation at a constant power level, up and down ramping within the range of available plant power, and the provision of constant reserve margins (e.g., constant megawatt headroom, percentage of rated capacity).

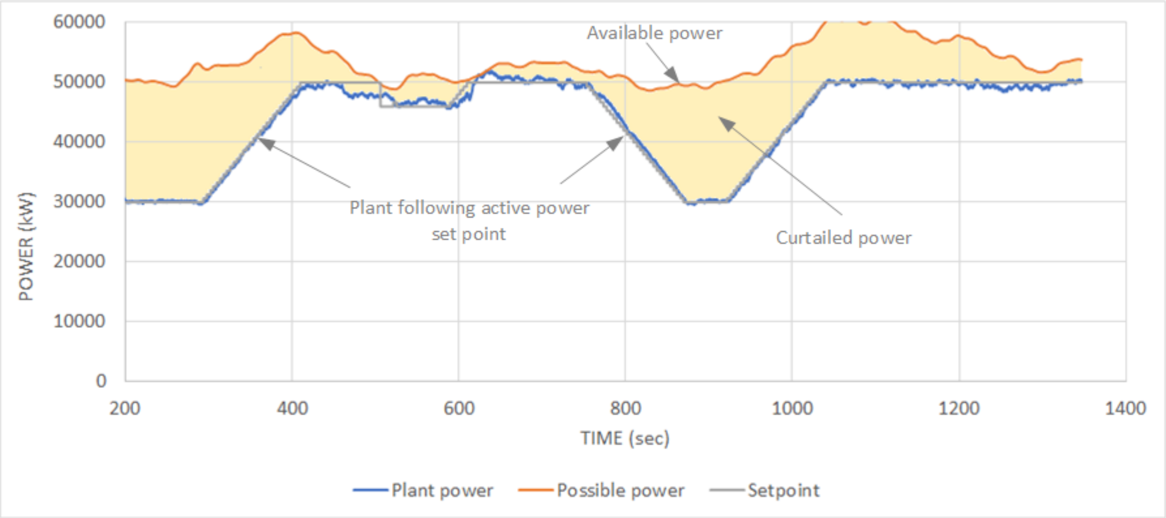

Figure 12. APC test (Source: NREL)

6.2.2 Active Power Control Test Results

Figure 13 and Figure 14 show two tests for controlled curtailment from a given megawatt output to zero power at a constant ramp rate followed by ramping up from zero to a given megawatt output. The first test shows the mode when the plant followed the down-ramp signal from the operator to curtail its production to zero power. During the curtailment process, several wind turbines were automatically instructed to go off-line until the plant approached zero output.

During the recovery process to maximum production, however, the upward and downward ramps were not symmetric even though the same ramp rate was applied. This is because the plant controller was operating in a mode with an end goal to achieve the peak power production only at the end of the production restoration interval. During this time, many individual wind turbines remained off until the end of the interval, as shown in Figure 13, so the production recovery process had two large steps.

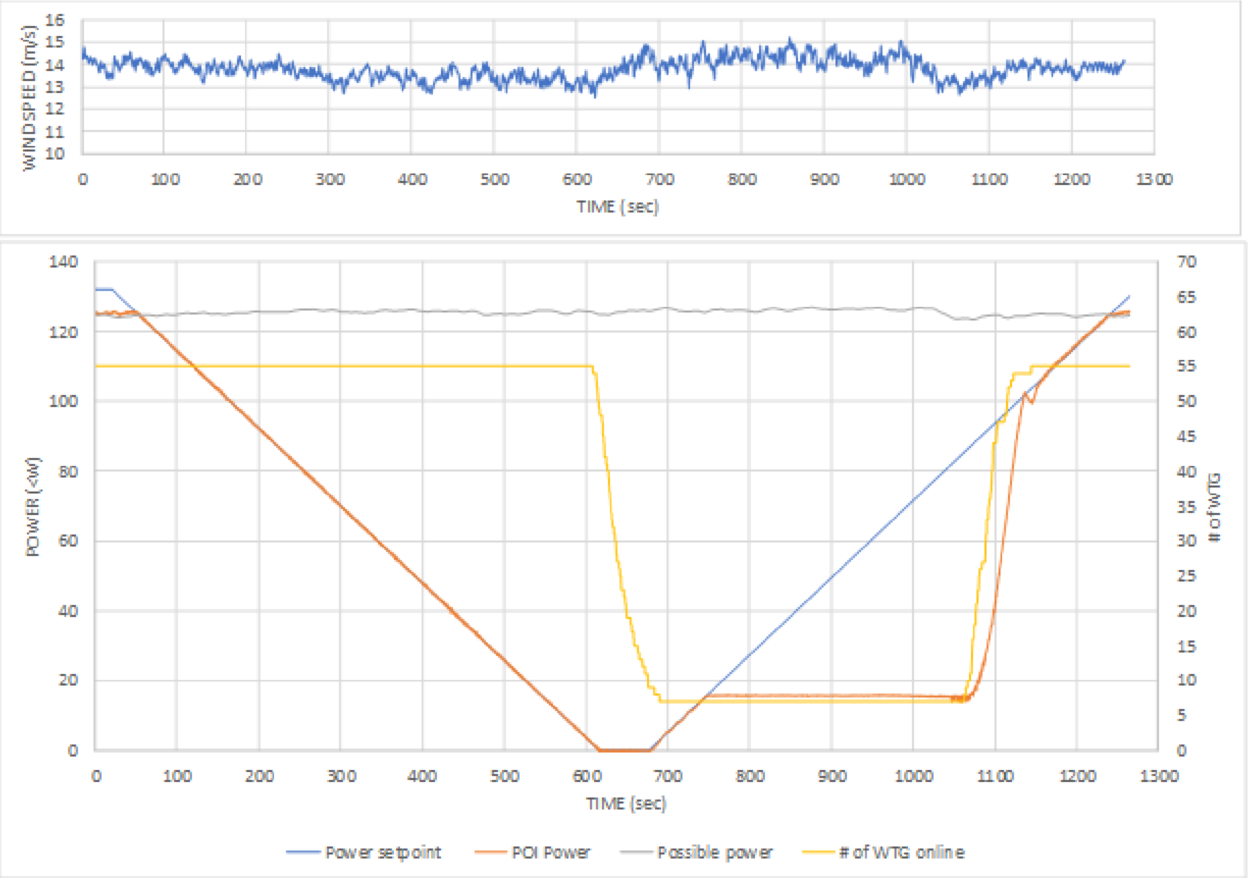

Figure 13. Curtailment Test 1

During the second test, the plant controller was instructed to ramp down from full production to 20 MW and then ramp up to full production using the same ramp rate. As shown in Figure 14, the plant was able to precisely follow the downward and upward set points.

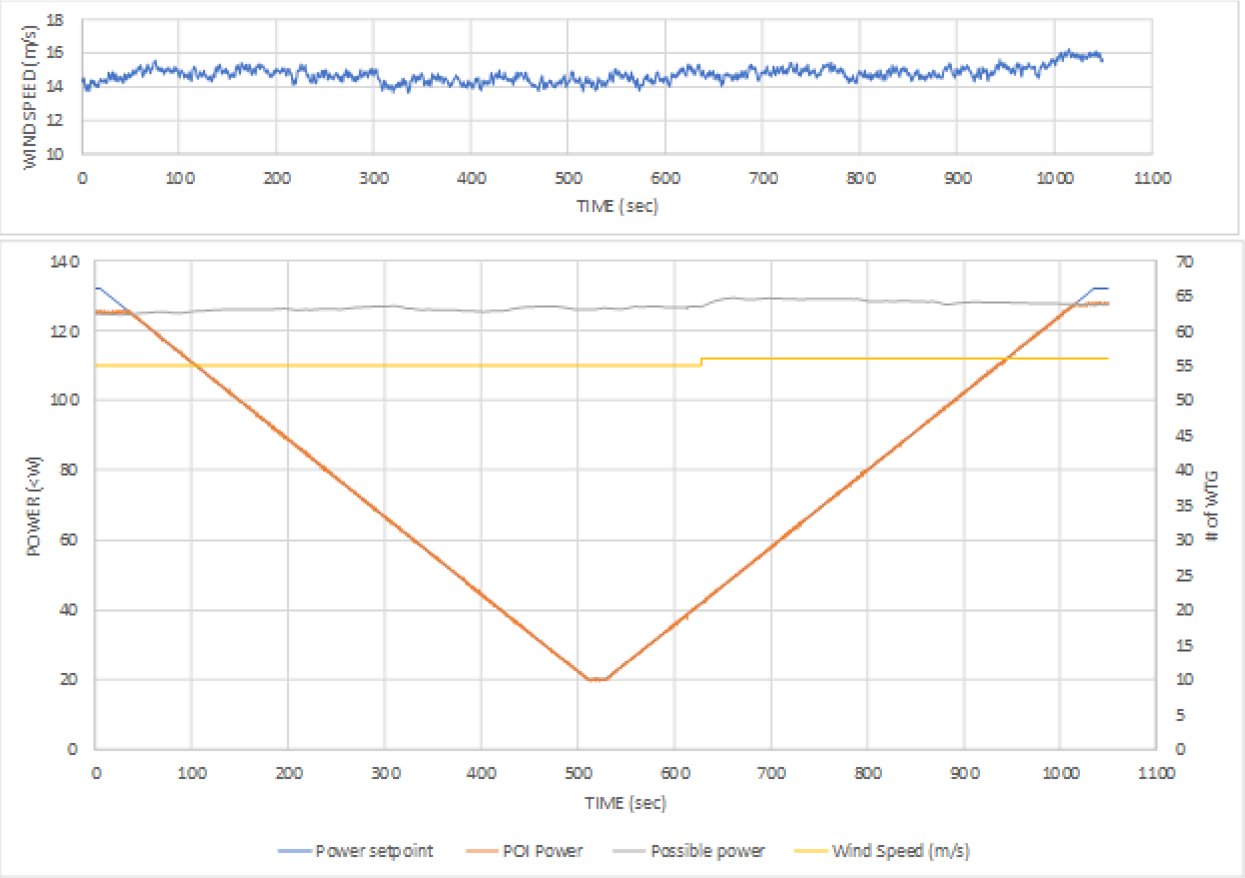

Figure 14. Curtailment Test 2

During both tests, the plant demonstrated the ability to accurately follow the active power set point for different control objectives.

6.2.3 Automatic Generation Control Test Results

Frequency regulation is provided by online generation whose output is typically changed on a 4-second basis through a balancing authority's AGC system and/or by other nongenerating resources, such as flywheels or energy storage resources that can provide regulation service.

An AGC system adjusts the power output of multiple generators in the power system in response to a change in the system loads (normally every 4 seconds) in a bulk power grid. Several tests were conducted to measure the WPP's ability to follow a 4-second active power set point signal from CAISO that communicated with the WPP PPC.

Because the plant under test was not participating in CAISO's real-time AGC market, the adopted method of mimicking AGC provides enough approximation of real conditions because both the up-regulation and down-regulation characteristics of the plant can be tested.

In CAISO's market, resources providing regulation services are compensated in accordance with Federal Energy Regulatory Commission (FERC) Order 755 [7], whereby resources receive a capacity payment that reflects the marginal resource's opportunity costs during the settlement period and a performance payment that reflects the amount of up and down movement the resource provides in response to the system operators dispatch.

FEDERAL ENERGY REGULATORY COMMISSION ORDER 755

On October 11, 2011, the Federal Energy Regulatory Commission issued Order 755, which established a two-part market-based rate compensation methodology for the provision of frequency regulation service in regional transmission operator and independent system operator markets. Resources are compensated for providing regulation service through (1) a capacity payment that reflects the marginal resource's opportunity costs during the settlement period and (2) a performance payment that reflects the amount of up and down movement the resource provides in response to the system operators dispatch signal and the resource's accuracy in responding to the dispatch signal.

The AGC test results shown in Figure 15 and Figure 16 depict good linear correlation between the commanded and measured plant power output.

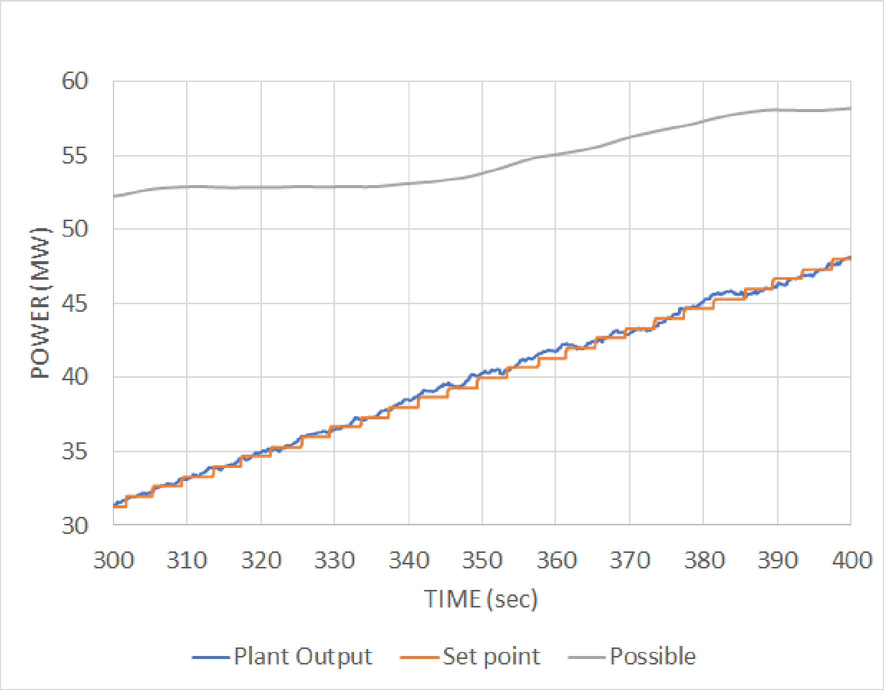

Figure 15. Test 1: Tule Wind Farm following 4-second AGC-like signal from CAISO

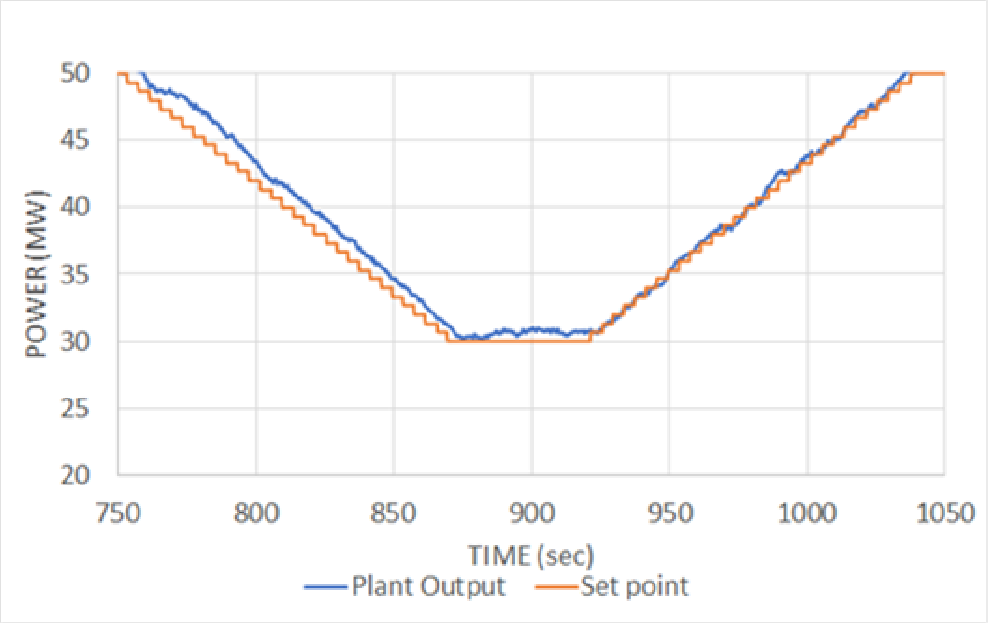

Figure 16. Test 2: Tule Wind Farm following 4-second AGC-like signal from CAISO

The relative AGC control error as a percentage of installed plant capacity for the conducted AGC test is shown in Figure 17. The maximum values of AGC control error are within ±2% of the plant rated capacity. Such control accuracy is consistent with accuracy that was demonstrated by a 300-MW PV power plant during similar testing project conducted in 2016 [18].

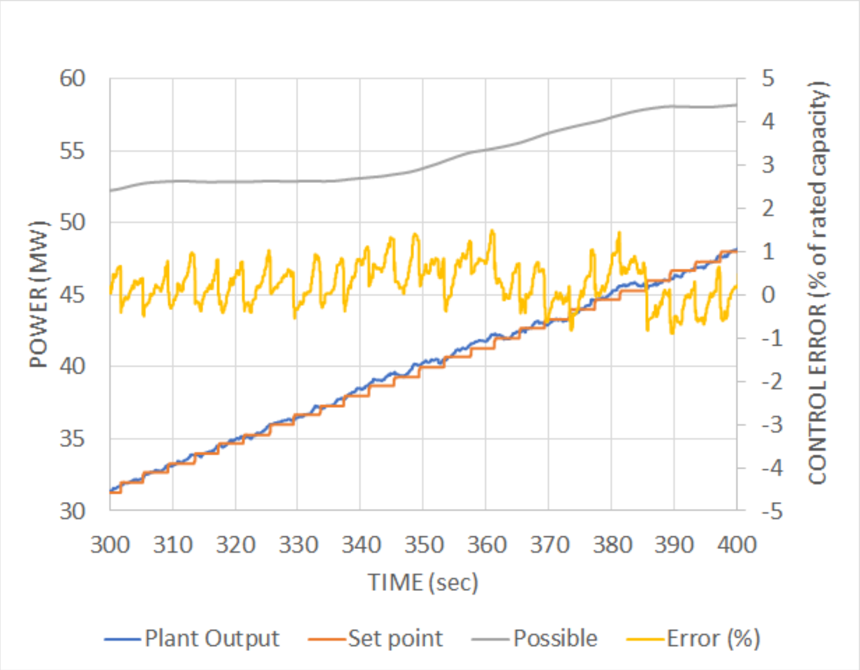

Figure 17. Accuracy of AGC control

Normally, CAISO measures the accuracy of a resource's response to energy management system (EMS) signals during 15-minute intervals by calculating the ratio between the sum of the total 4-second set point deviations and the sum of the AGC set points. By comparing the WPP testing results from the values for individual technologies, a conclusion was made that regulation accuracy by the WPP plant is 25–35 points better than fast gas turbine technologies, and very similar to the performance by utility-scale PV power plants (Figure 18). The blue bars reflect the annual average for the existing fleet.

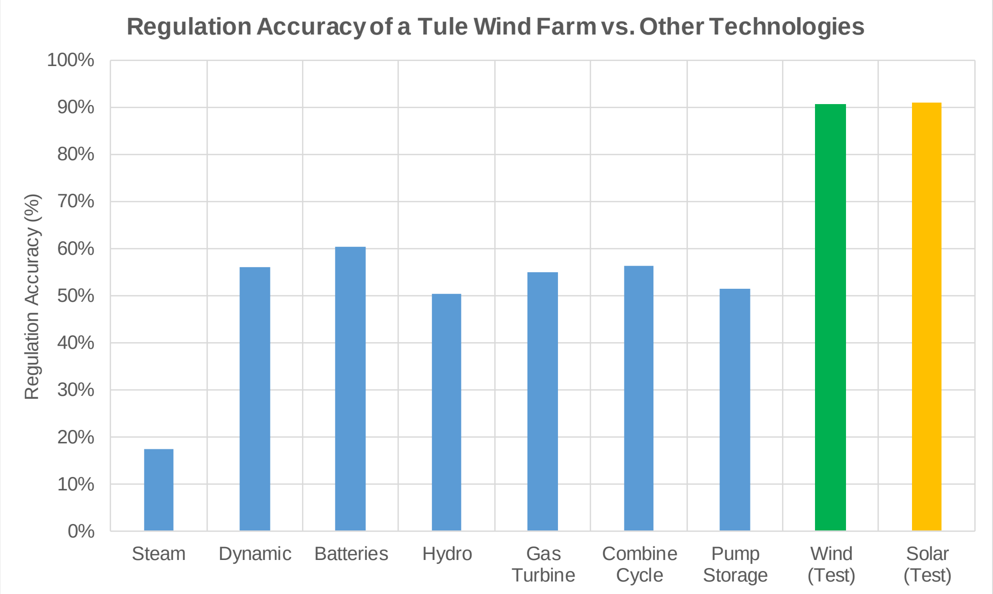

Figure 18. Comparison of typical regulation accuracy of CAISO conventional generation

7. Frequency Control

Several research projects demonstrated that the frequency response in the Western Interconnection is not in a major crisis—at least until extremely high penetrations of renewable generation are present [8], [9]. In fact, the frequency response (MW/0.1 Hz) of the Western Interconnection is gradually improving, according to a trend published by NERC and shown in Figure 19. The chart shows the frequency response of many recorded events in the Western Interconnection from 2012 through 2018 [10].

For the data set, the regression line has a small positive slope, meaning that the frequency response shows a slowly increasing trend over time. It is important to realize, however, that even if the overall frequency response of the Western Interconnection is satisfactory, the ability of certain balancing authorities, such as CAISO, to meet their frequency response obligation and frequency regulation metrics can be challenging during certain load and variable generation scenarios. In this regard, the frequency-responsive controls of WPPs—along with PV plants and energy storage systems—can help address this issue.

CAISO's analysis of actual frequency response following actual frequency events shows that on days with high renewable generation production and low loads, maintaining adequate resources with enough headroom to meet the primary frequency response obligation is a challenge.

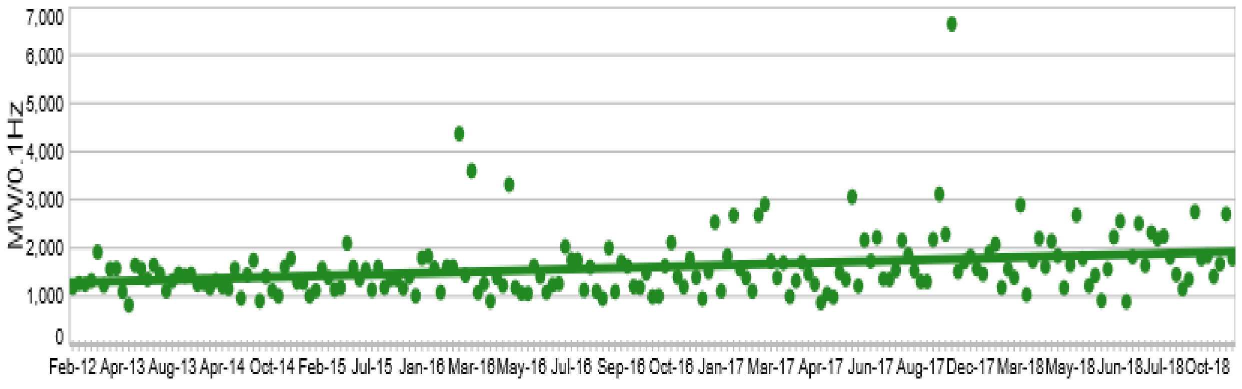

Figure 19. Trend of Western Interconnection frequency response (Source: NERC)

7.1 *Rationale and Description of Frequency Droop Tests*

The ability of a balancing authority to support the interconnection frequency within a safe operating range is crucial for system stability and reliability. Frequency response is a measure of an interconnection to respond to a variety of contingency events to ensure rapid restoration of the balance between generation and load and to stabilize the frequency following the sudden loss of generation or load.

On January 16, 2014, FERC approved Reliability Standard BAL-003-1 (Frequency Response and Frequency Bias Setting), submitted by NERC. With the approval of this standard, NERC created a new obligation for balancing authorities, including CAISO, to demonstrate that they have enough frequency response to respond to disturbances resulting in the decline of system frequency. The purpose of this initiative is to ensure that balancing authorities provide enough PFR to support system reliability while complying with this NERC requirement [11].

NERC determined that the Western Interconnection frequency response obligation is based on the largest potential generation loss of two Palo Verde generating units (2,626 MW). NERC created this standard to ensure that balancing authorities have enough frequency response capability to prevent the loss of load following the worst credible contingency in an interconnection. Like all balancing authorities, CAISO must have an adequate amount of frequency response capability available to respond to actual frequency events in real time. For 2019, CAISO's frequency response obligation was 193.7 MW/0.1 Hz [12].

FEDERAL ENERGY REGULATORY COMMISSION ORDER 842

On February 15, 2018, the Federal Energy Regulatory Commission issued Order 842, revising its regulations to require newly interconnecting large and small generating facilities—both synchronous and nonsynchronous—to install, maintain, and operate equipment capable of providing primary frequency response as a condition of interconnection. The final rule also amends the commission's pro forma interconnection agreements to include certain operating requirements, such as maximum droop and deadband parameters, as well as sustained response provisions. It provides exemptions for nuclear power plants and some combined heat-and-power plants.

Based on historical events during 2019, CAISO recognized that its median frequency response rate could fall short of its FRO by as much as 85 MW/0.1Hz. From this perspective, participation of curtailed wind and PV power plants in providing frequency response could help address this potential deficiency. The objective of the frequency response test conducted under this project is to demonstrate that the plant can provide a response in accordance with 5% and 4% droop settings through its governor-like control system. The definition of implemented droop control for a wind plant is the same as that for conventional generators:

$$Droop = \frac{\Delta P / P_{rated}}{\Delta f / 60Hz} \tag{2}$$

Tule WPP rating of 131.1 MW is used in equation (2) for the droop-setting calculations. For the droop test, the plant was set to operate at a curtailed power level that was 20 MW less than the available estimated peak power capability. The PPC was programmed to change the power output of the plant in accordance with a symmetric droop characteristic, shown in Figure 20.

The upper limit of the droop curve was the available plant power, and the lower limit was at a level that was approximately 20 MW less than the available peak power at the time. The droop curves for the plant were tested at frequency deadbands of ±36 mHz and ±16 mHz.

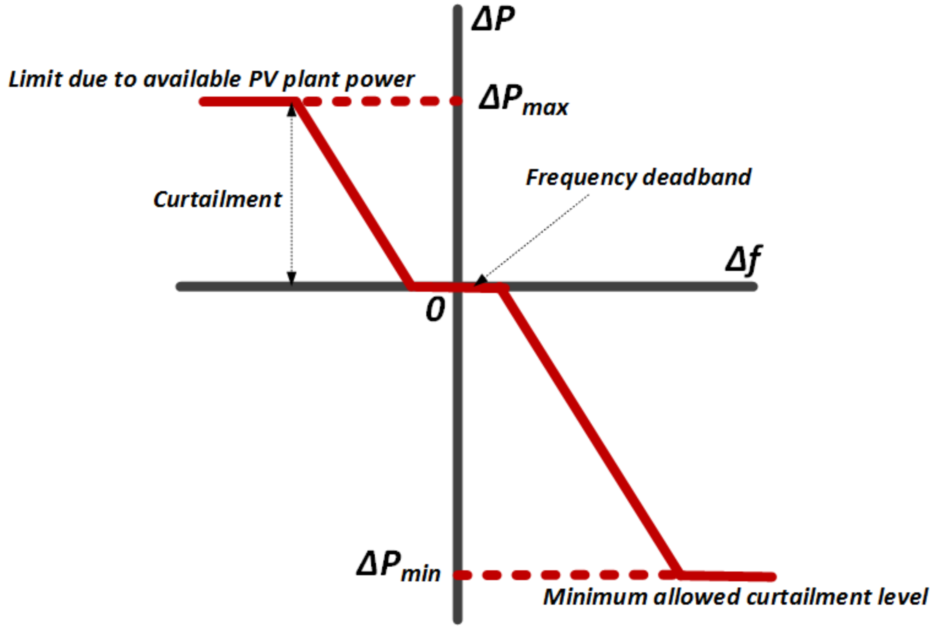

Figure 20. Frequency droop characteristic (Source: NREL)

A wind turbine must operate in a curtailed mode to provide enough reserve for PFR during under-frequency conditions. During normal operating conditions with near-nominal system frequency, the control is set to provide a specified margin by generating less power than is available from the unit. The reserve available (or “headroom”) is the available power curtailed, which is shown in Figure 21 as the reserve between the operational point and *P*0. Figure 21 also shows that a non-symmetric droop curve is possible with wind power, depending on system needs.

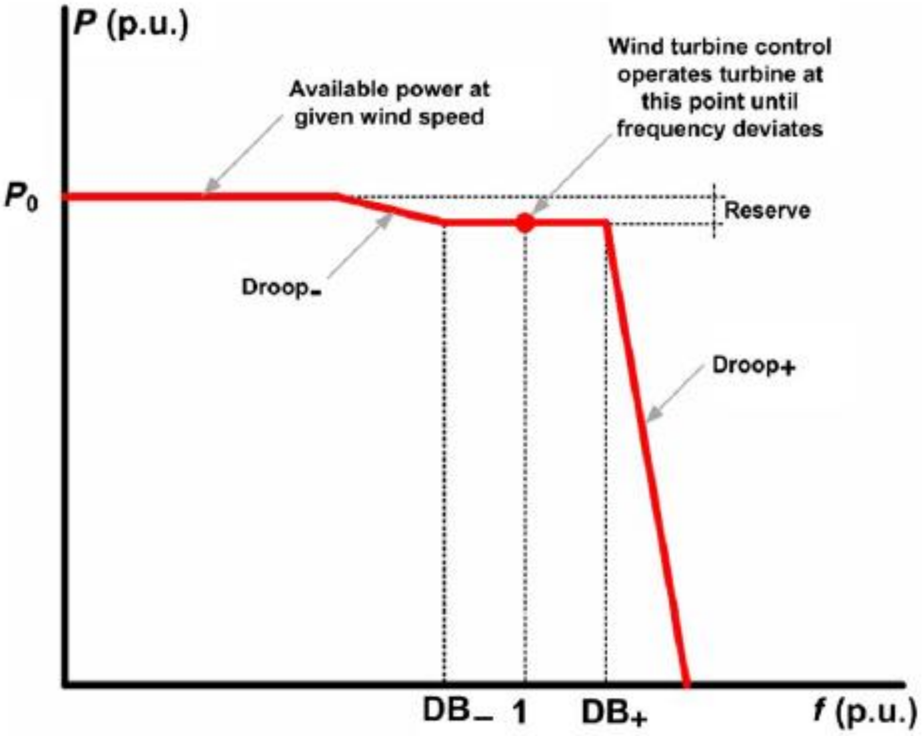

Figure 21. Nonsymmetric droop characteristic of a WPP (Source: NREL)

The frequency droop capability of the plant was tested using the actual over- and under-frequency events that occurred in the Western Interconnection as measured by the National Renewable Energy Laboratory (NREL) in Colorado.

The setup for simulating the recorded frequency events is shown in Figure 22. An NREL laptop with recorded time-series files for frequency events was connected to a National Instruments' USB-to-analog output card. The analog output card was wired directly to the positive and negative terminals of the designated analog input card.

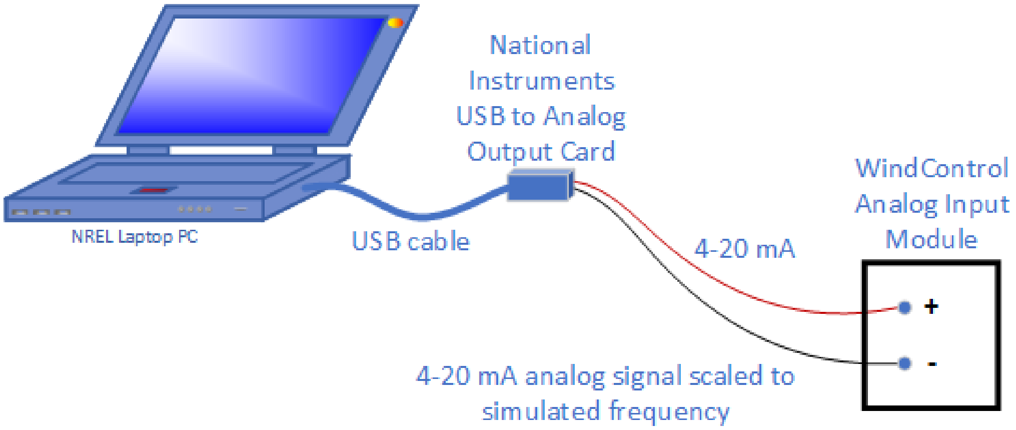

Figure 22. Feeding a grid frequency signal to WindCONTROL (Source: NREL)

The card produces a 4–20 mA signal that can be scaled to any desired frequency levels. The scaling multiplier and offset were calculated from the data provided by the GE team (for example: 60 Hz = 12 mA, 59 Hz = 6 mA).

The frequency event shown in Figure 23 was for an actual Western Interconnection event recorded by NREL's frequency monitoring system. This event started after a large generation loss at *t* = 0 seconds. The value at Point A is the pre-disturbance frequency, and it was calculated as an average of frequency values from *t* = 0 to *t* = −16 seconds. The grid frequency started declining immediately following the generation loss because of an imbalance between generation and load. The initial rate of change of frequency was approximately −63 mHz/s, and this was determined by the amount of rotating mass in the Western Interconnection. The PFR from conventional generation started to respond immediately after the frequency decline passed beyond the governor deadband thresholds. The characteristics of system inertia and PFR determine the lowest frequency (nadir), which is shown as Point C.

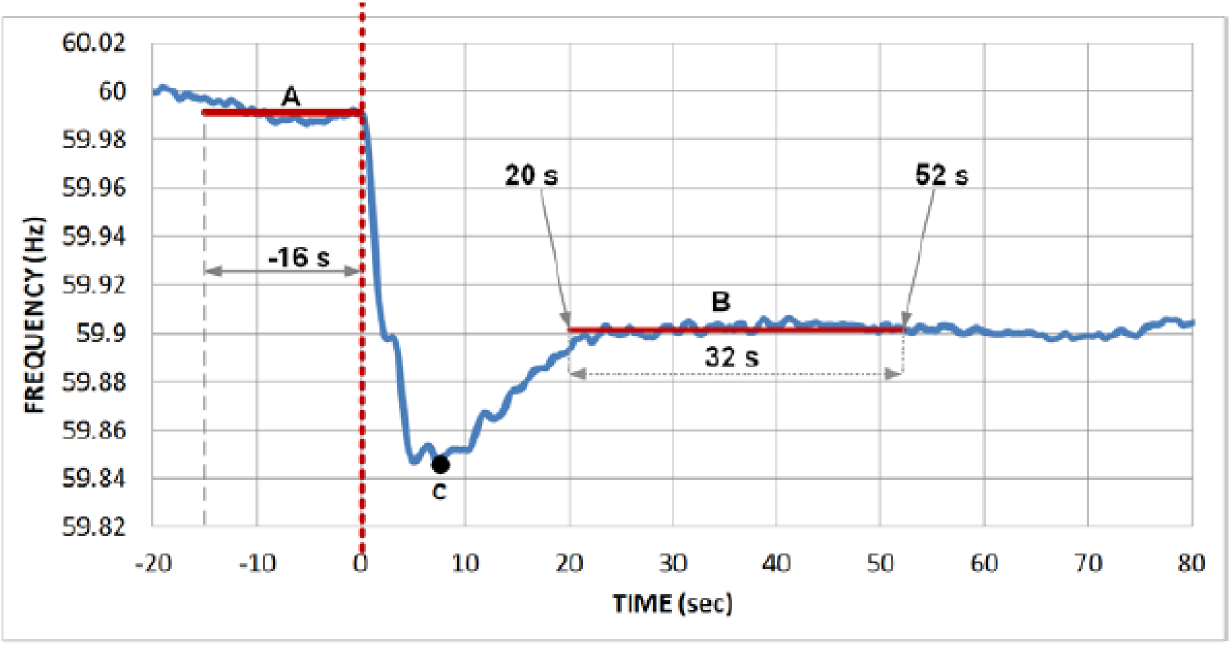

Figure 23. Example of a frequency event measured in the Western Interconnection (Source: NREL)

Important characteristics following a disturbance are system inertia, amount of PFR headroom, and the response speed of PFR. Interconnections ensure that Point C is higher than the highest set point for under-frequency load shedding within an interconnection. Point C is based on the largest credible N-2 contingency in an interconnection. After the frequency decline has been arrested, continued delivery of PFR will stabilize the system frequency to a steady state (Point B). The point at which frequency is stabilized is often referred to as steady-state frequency. The B value is determined by averaging the frequency values from a period of 32 seconds starting at *t* = 20 seconds after the disturbance.

The goal of the demonstration project described in this report is to provide "real-world" data from a utility-scale WPP that can help assess the impact of wind generation on the frequency response of a single balancing authority or the interconnection. The following frequency metrics can be evaluated for a whole interconnection by proper modeling of frequency-responsive services by wind power, as was demonstrated by this project:

- Initial rate of decline of frequency
- Value of frequency nadir (Point C)
- Transition time between the beginning of the disturbance and the frequency nadir (transition time from Point A to Point C)
- Value of settling frequency (Point B)
- Transition time between the frequency nadir and the settling frequency (transition time from Point C to Point B).

According to the FERC BAL-003-1 standard, many comments used to calculate the interconnection frequency response obligation are from statistical observations of actual frequency events. Various parameters—including the starting frequency, first step of under-frequency load shedding, contingency criteria, withdrawal adjustment, ratio of frequency value at Point C to value at Point B (CB*R*), and demand response credit—are used in interconnection frequency response obligation calculations.

7.2 Test Results: Droop Settings of 5% and 4%

The GE team remotely programmed the PPC in droop control modes of 5% and 4% with approximately 20 MW of power curtailment. The droop control implemented at the Tule WPP was originally designed to satisfy grid codes that activated on a timescale from 5 seconds to 20 seconds; therefore, the deadband setting did not play much role in how the WPP was responding to the frequency event because its response time was activated at much lower frequencies than the 16 mHz or 36 mHz deadbands. While not implemented at the Tule WPP, it should be noted that GE does provide software solutions to support higher speed responses to frequency events when required by grid operators.

The initial prefault grid frequency (Point A) was at approximately 60.02 Hz. The frequency started to decline following a generation loss in the Western Interconnection; however, the WPP response was activated approximately 2–3 seconds after the beginning of the event. Once activated, the WPP power output essentially followed the frequency proportional to 5% droop settings. After reaching the frequency nadir (Point C), at t ≈ 8 seconds, the WPP deployed its primary reserves in accordance with the value of the settling frequency (Point B), which was an average of 20–52 seconds after the generation loss.

7.3 Under-frequency Test Results

The Tule WPP demonstrated consistent droop performance during several under-frequency tests for both the 5% and 4% droop settings, as shown in Figure 24. Figure 24 also shows the test parameters measured after each test.

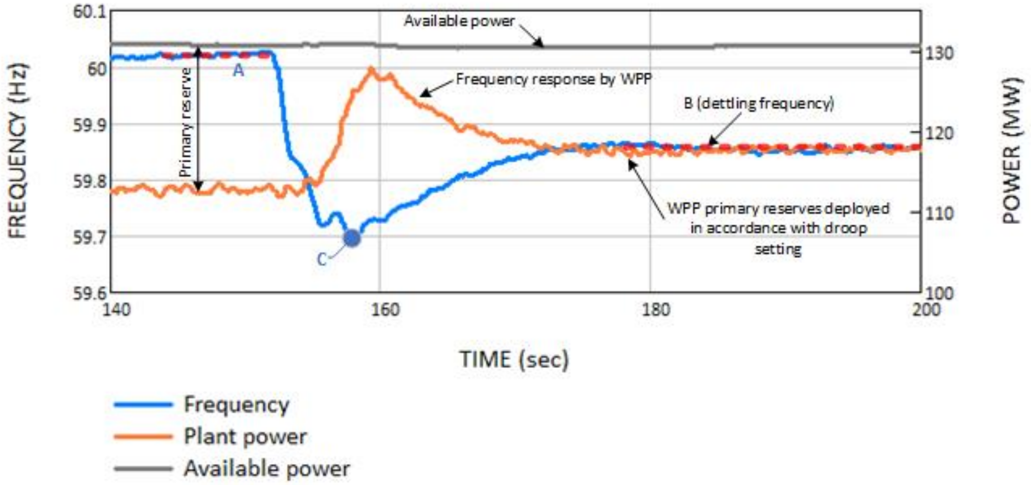

Figure 24. Tests parameters measured

7.3.1 *Test 1: Under-frequency (5% Droop and 36 mHz)*

Test 1 was conducted with the Tule WPP curtailed by 15% of its maximum production capability at the time of the test. The droop-like setting was set at 5%, and the frequency deadband was set at 36 mHz. Following the event, the maximum frequency response within the first 20 seconds was 15.36 MW.

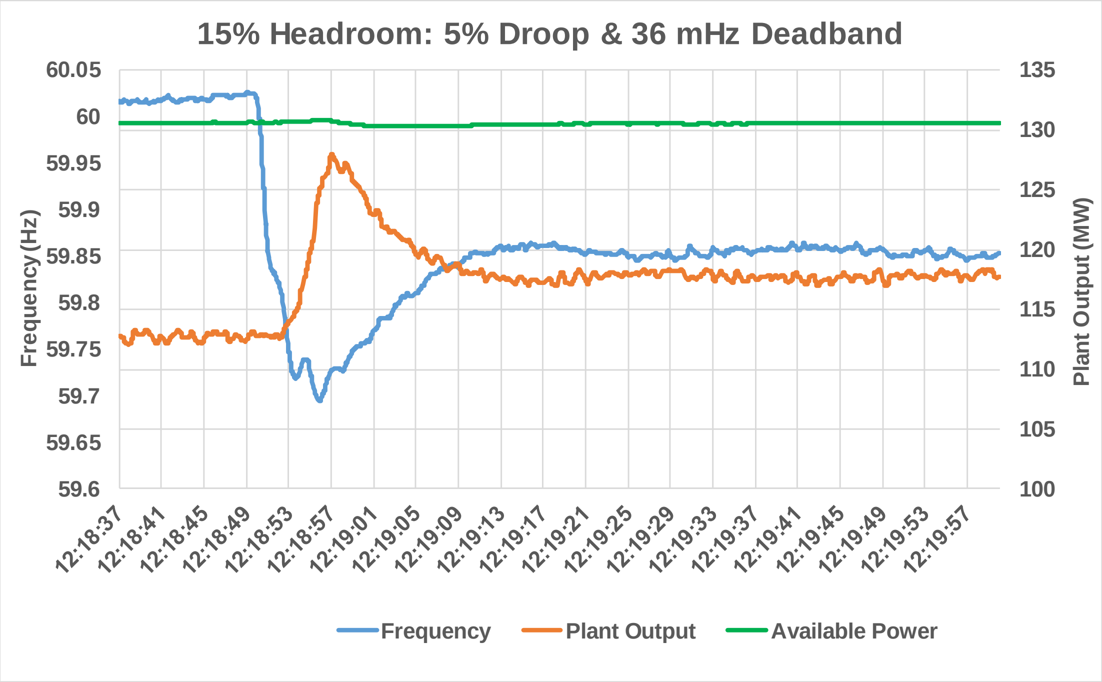

Figure 25. Test 1: Under-frequency event (5% droop and 36 mHz deadband)

7.3.2 *Test 2: Under-frequency (5% Droop and 16 mHz)*

The second test shows the Tule WPP curtailed by 15% of its maximum capability. The droop-like setting was set at 5%, and the frequency deadband was set at 16 mHz. The maximum frequency response within the first 20 seconds following the disturbance was 16.09 MW.

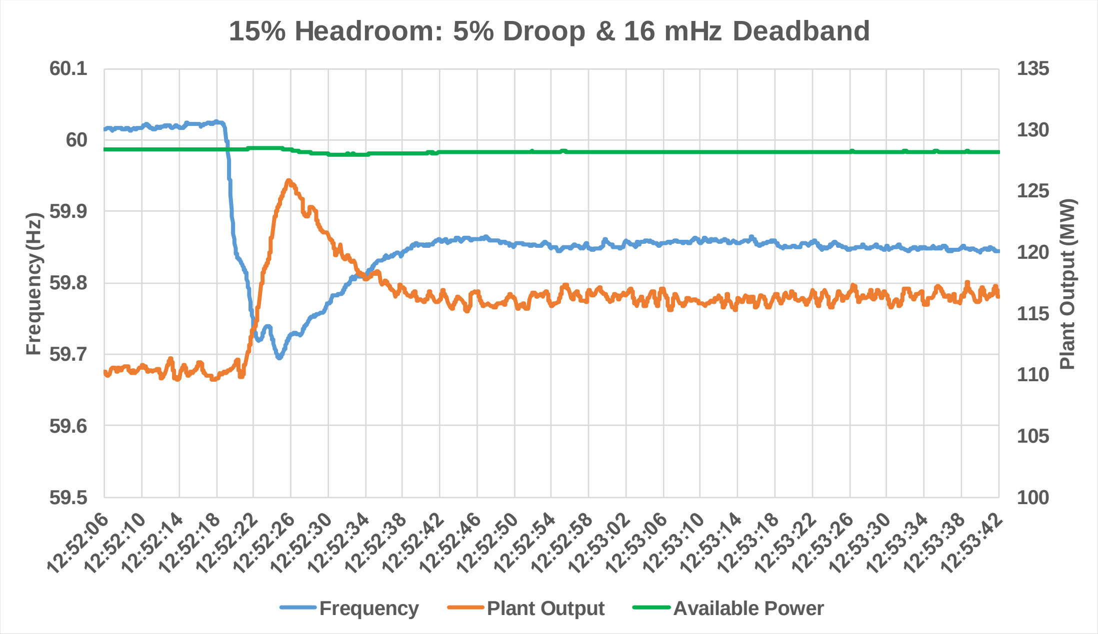

Figure 26. Test 2: Under-frequency event (5% droop and 16 mHz)

7.3.3 *Test 3: Under-frequency (4% Droop and 36 mHz)*

The third test was conducted with the Tule WPP curtailed by 15% of its maximum capability. The droop-like setting was set at 4%, and the frequency deadband was set at 36 mHz. The maximum frequency response within the first 20 seconds following the disturbance was 17.83 MW.

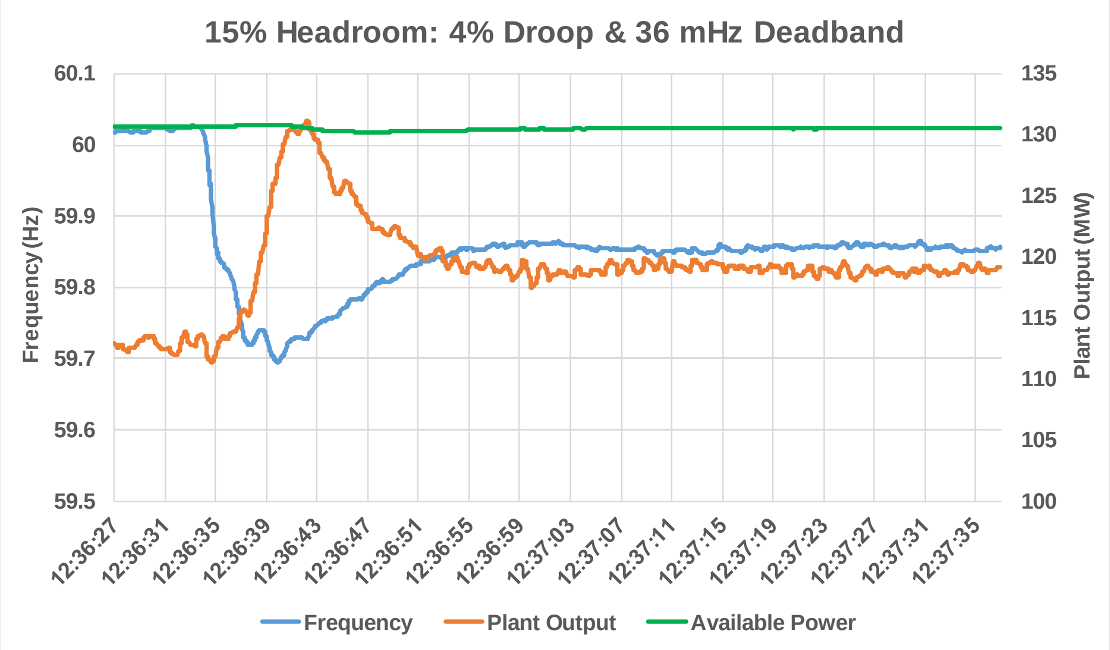

Figure 27. Test 4: Under-frequency event: 4% droop and 36 mHz)

7.3.4 Test 4: Under-frequency (4% Droop and 16 mHz)

The fourth test was conducted with the Tule WPP curtailed by 15% of its maximum capability. The droop-like setting was set at 4%, and the frequency deadband was set at 16 mHz. The maximum frequency response within the first 20 seconds following the disturbance was 19.32 MW.

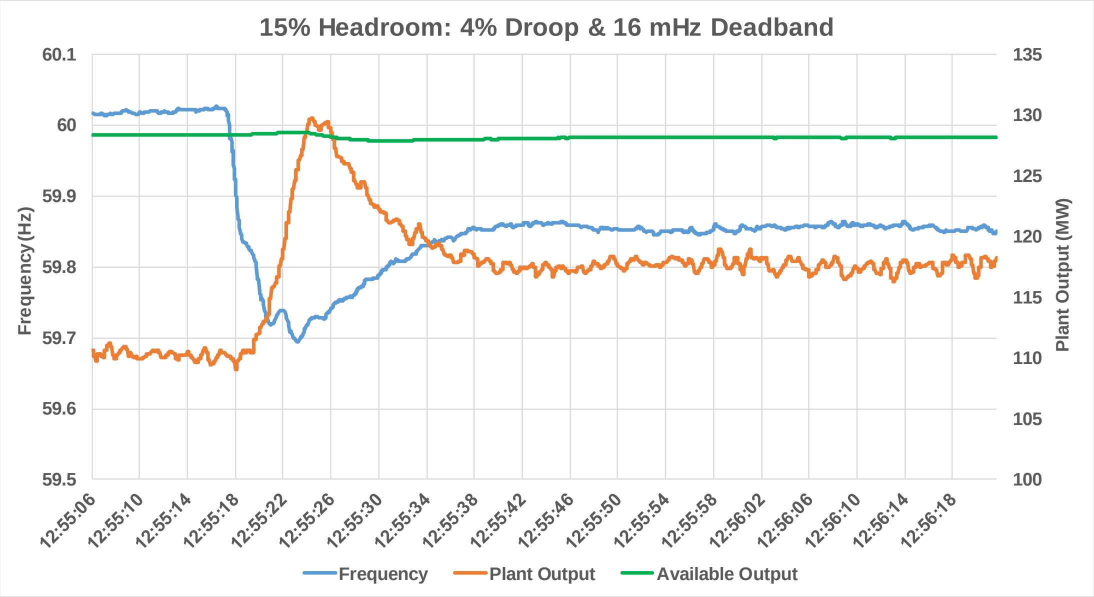

Figure 28. Test 4: Under-frequency event: (4% droop and 16 mHz)

7.4 Comparison of Under-frequency Events

Table 1. Comparison of Various Droop and Deadband Settings for the Under-frequency Events

	5% Droop & 36 mHz Deadband	5% Droop & 16 mHz Deadband	4% Droop & 36 mHz Deadband	4% Droop & 16 mHz Deadband
Max Frequency Response within the first 20 seconds (MW)	15.36	16.09	17.83	19.32

As shown in Table 1, within the first 20 seconds following a low-frequency event, a droop setting of 4% and a deadband of 16 mHz provides the maximum frequency response, which is approximately 3.9 MW higher than CAISO's current inverter base settings of 5% droop and 36 mHz.

7.5 Under-frequency: Comparison of 5% Droop vs. 4% Droop

Figure 29 shows a comparison of 5% droop and 36 mHz (Test 1) and 4% droop and 36 mHz (Test 3). As shown for the same low-frequency event, a 4% droop setting provides approximately 3.96 MW higher frequency response than a 5% droop setting.

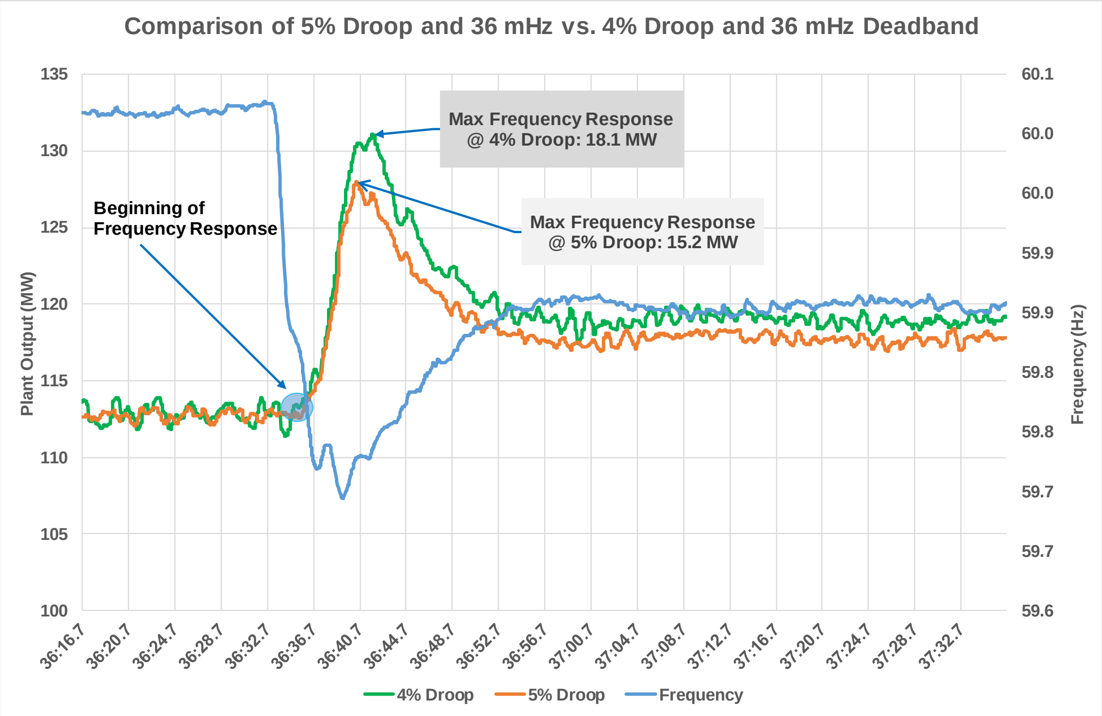

Figure 29. Comparison of frequency response at 5% droop vs. 4% droop

7.5.1 Frequency Response at 4% Droop and 36 mHz vs. 16 mHz Deadband

As shown in Figure 30, frequency response with a 4% droop and 16 mHz deadband is approximately 1.4 MW higher than a 4% droop and 36 mHz deadband for the same frequency event.

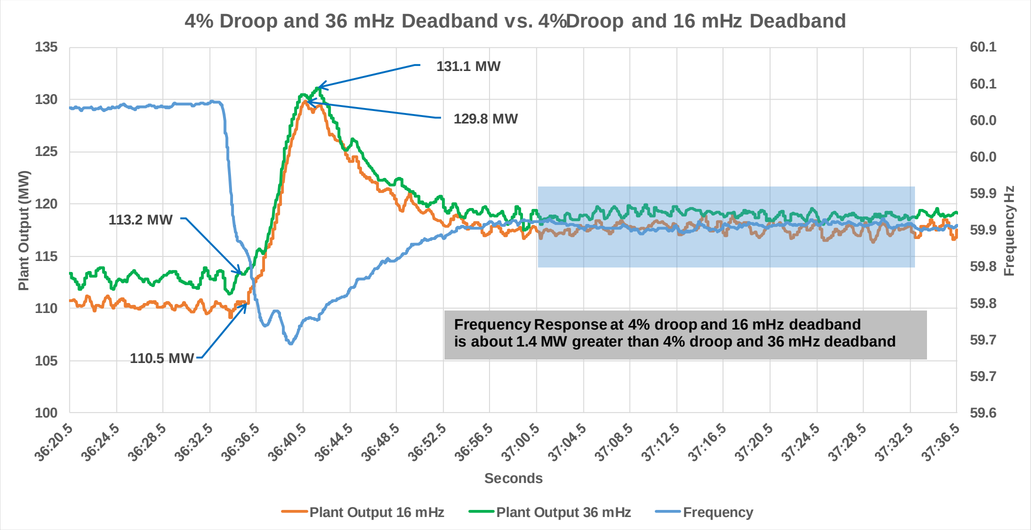

Figure 30. Four percent droop and 36 mHz deadband vs. 4% droop and 16 mHz deadband

7.5.2 Steady-State Frequency at 4% Droop and 36 mHz vs. 16 mHz Deadband

A closer look at the blue shaded area in Figure 30 shows that with a 16 mHz deadband, the response of the plant was greater than the response with a 36 mHz deadband for the same frequency deviations.

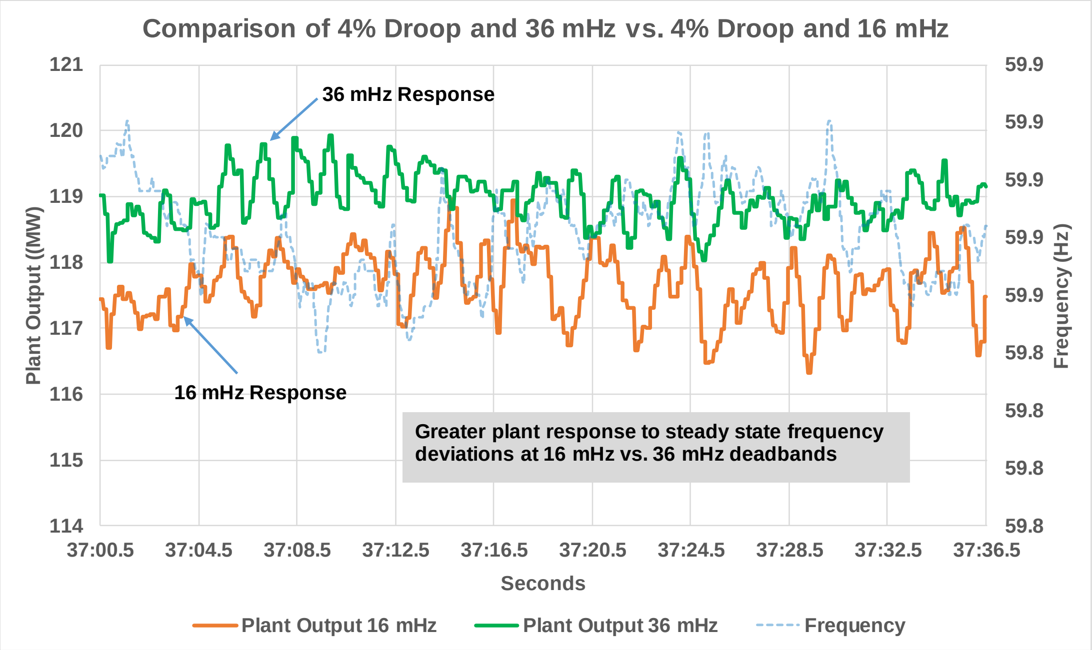

Figure 31. Comparison of 4% droop and 36 mHz vs. 4% droop and 16 mHz

7.6 Over-frequency Test Results

Several over-frequency tests were also conducted using the 4% and 5% droop settings with 36 mHz and 16 mHz deadbands. In general, no headroom was needed for the over-frequency tests.

7.6.1 Test 5: Over-frequency (5% Droop and 36 mHz)

The fifth test was conducted with the Tule WPP operating at its maximum capability. The droop-like setting was set at 5%, and the frequency deadband was set at 36 mHz. The maximum frequency response (curtailment) of the plant within the first 20 seconds of the event was 13.02 MW.

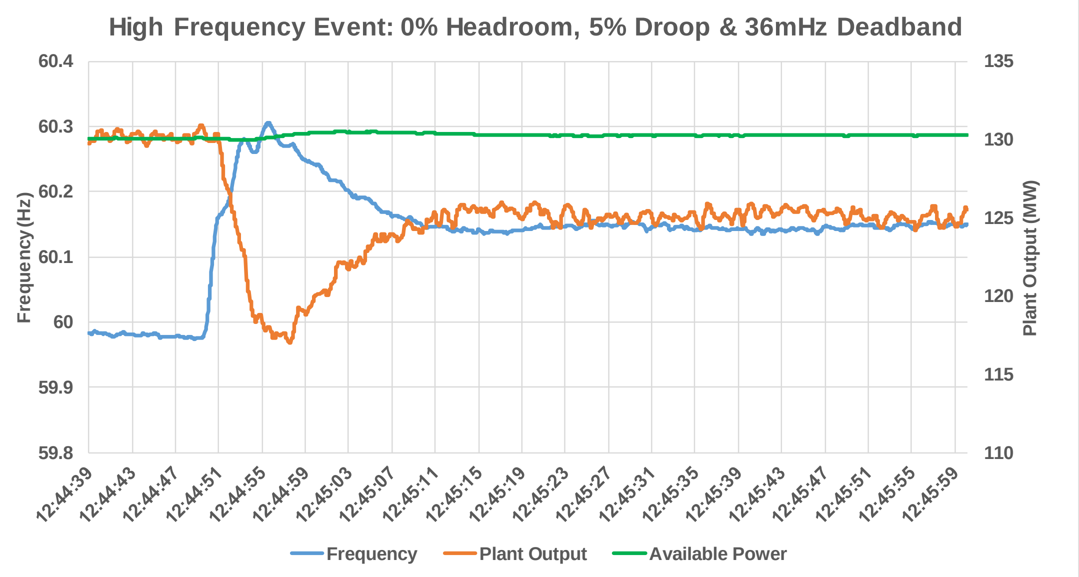

Figure 32. Test 7: Over-frequency event (5% droop and 36 mHz deadband)

7.6.2 Test 6: Over-frequency (5% Droop and 16 mHz)

The sixth test was conducted with the Tule WPP operating at its maximum capability. The droop-like setting was set at 5%, and the frequency deadband was set at 16 mHz. The maximum frequency response (curtailment) of the plant within the first 20 seconds of the event was 14.14 MW.

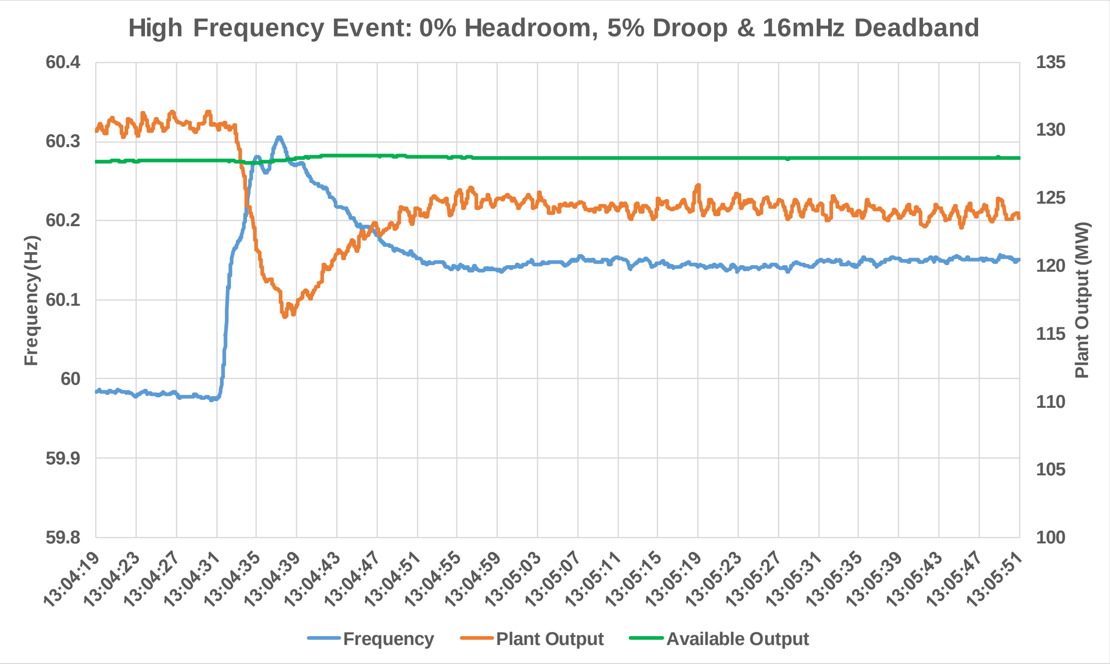

Figure 33. Test 8: Over-frequency event (5% droop and 16 mHz deadband)

7.6.3 Test 7: Over-frequency (4% Droop and 36 mHz)

The seventh test was conducted with the Tule WPP operating at its maximum capability at the time. The droop-like setting was set at 4%, and the frequency deadband was set at 36 mHz. The maximum frequency response (curtailment) of the plant within the first 20 seconds of the event was 16.89 MW.

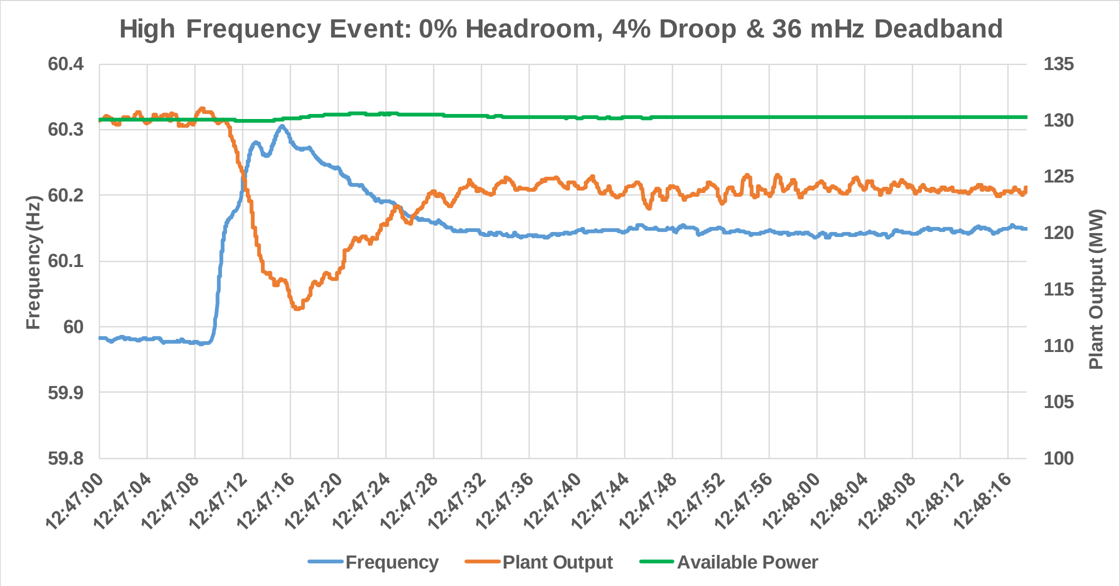

Figure 34. Test 9: Over-frequency event (4% droop and 36 mHz deadband)

7.6.4 Test 8: Over-frequency (4% Droop and 16 mHz)

The eighth test was conducted with the Tule WPP operating at its maximum capability at the time. The droop-like setting was set at 4%, and the frequency deadband was set at 16 mHz. The maximum frequency response (curtailment) of the plant within the first 20 seconds of the event was 18.0 MW.

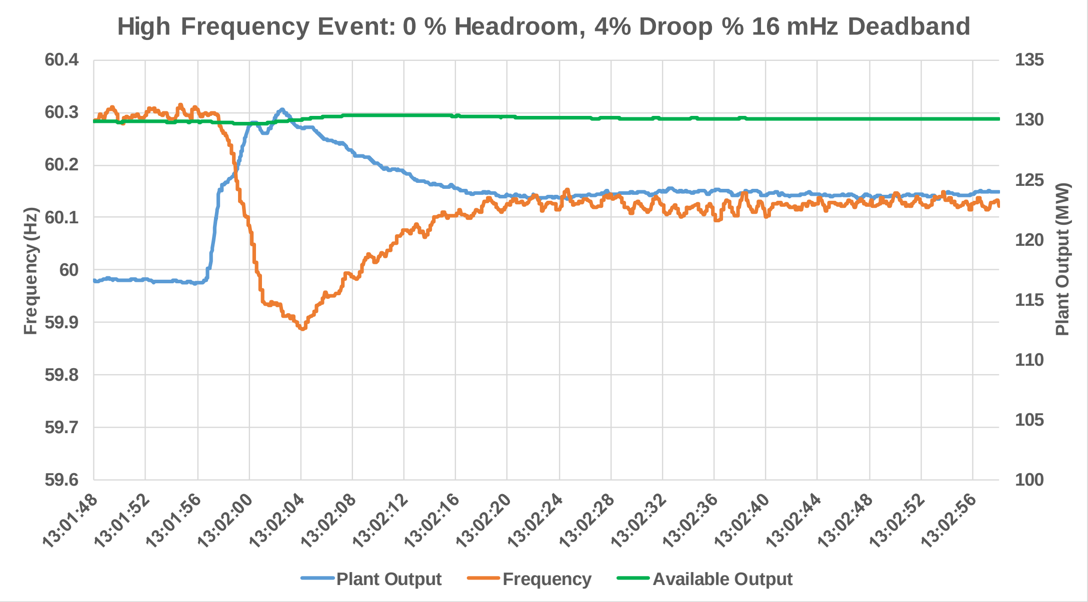

Figure 35. Test 8: Over-frequency event: (4% droop and 16 mHz)

Because of favorable wind conditions at the Tule WPP during the day of frequency response testing (wind speed was steady and close to rated), the plant was operating on the flat portion of the equivalent power curve. Because of the limited time window available for such tests, no frequency response tests were conducted at lower wind speeds.

7.7 Comparison of Over-frequency Events

As shown in Table 2, within the first 20 seconds following the high-frequency events, a droop setting of 4% and a deadband of 16 mHz provides the maximum frequency response (curtailment), which is approximately 4.9 MW higher than CAISO's current inverter base settings of 5% droop and 36 mHz.

Table 2. Comparison of Various Droop and Deadband Settings for Over-frequency Events

	5% Droop and 36 mHz Deadband	**5% Droop and 16 mHz Deadband**	**4% Droop and 36 mHz Deadband**	**4% Droop and 16 mHz Deadband**
Max frequency response (curtailment) within the first 20 seconds (MW)	13.02	14.14	16.89	18.00

8. Reactive Power and Voltage Control Tests

8.1 Rationale and Description of Reactive Power Tests

FERC issued Order 827 on June 16, 2016, eliminating exemptions for newly interconnecting wind generators under its jurisdiction from the requirement to provide reactive power by revising the pro forma LGIA and the pro forma Small Generator Interconnection Agreement. FERC found that because of technological advancements, the cost of providing reactive power no longer creates an obstacle to wind power development, and the decline in cost resulted in the exemptions being "unjust, unreasonable, and unduly discriminatory and preferential."

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> All newly interconnecting nonsynchronous generators must "maintain a composite power delivery at continuous rated power output at the high-side of the generator substation… [and]… must provide dynamic reactive power within the power factor range of 0.95 leading to 0.95 lagging when operating more than 10% of the plant capacity, unless the transmission provider has established a different power factor range that applies to all nonsynchronous generators in the transmission provider's control area on a comparable basis."

Voltage on the North American bulk system is normally regulated by generator operators, which are typically provided with voltage schedules by transmission operators [13]. The growing penetration level of variable resources has led to the need for them to contribute to power system voltage and reactive regulation because in the past the bulk system voltage regulation was provided almost exclusively by synchronous generators. According to FERC's LGIA [14], the generally accepted power factor requirement of a large generator is ±0.95. In conventional power plants with synchronous generators, the reactive power range is normally defined as dynamic. So synchronous generators need to continuously adjust their reactive power production or absorption within a power factor range of ±0.95 to maintain a scheduled voltage.

Conventional synchronous generators have reactive power capability that is typically described as a "D curve," as shown in Figure 36. The reactive power capability of conventional power plants is limited by many factors, including their maximum and minimum load capability, thermal limitations because of rotor and stator current-carrying capacities, and stability limits. The ability to provide reactive power at zero loads is usually not possible with many large plant designs. Only some generators are designed to operate as synchronous condensers with zero actives loads. The reactive power capability of a wind inverter is determined by its current limit only. With proper MW and MVA rating, the wind inverter can operate at full current with reactive power capability, as shown in Figure 36.

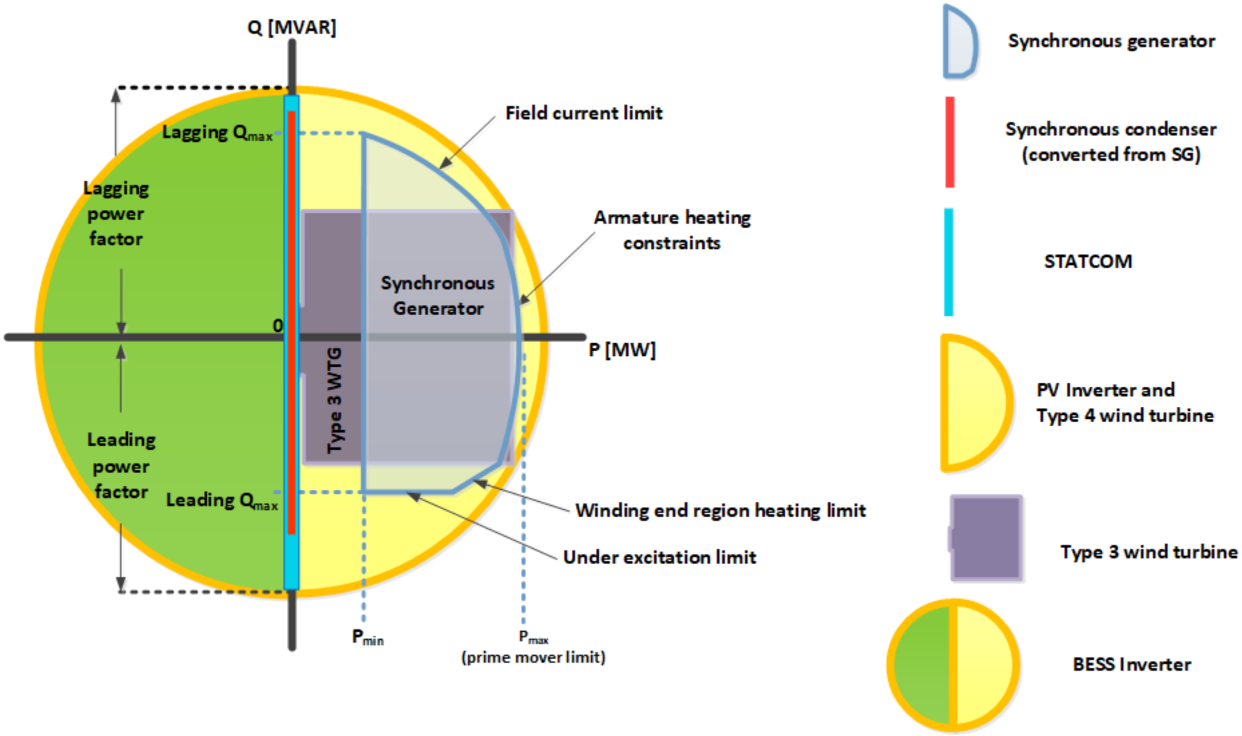

Figure 36. Notional comparison of reactive power capabilities for various technologies (Source: NREL)

The voltage at the POI or the high side of the plant step-up transformer bank could change because of grid conditions, but the plant must maintain its reactive power capability. For this purpose, the proposed CAISO reactive power requirement specifies a voltage operating window for the asynchronous generating facility to provide reactive power at 0.95 lagging power factor when voltage levels are between 0.95 p.u. and 1 p.u. Likewise, it should be able to absorb reactive power at 0.95 leading power factor when voltage levels are between 1 p.u. and 1.05 p.u. at the POI or high side of the step-up transformer bank.

The primary objective of the reactive power tests was to demonstrate the capability of the WPP to operate in voltage regulation mode within the 0.95 leading/lagging power factor range. The plant controller maintained the specified voltage set point at the high side of the generator step-up bank by regulating the reactive power produced by the inverters.

8.2 Results of Reactive Capability Power Tests

GE's WindFREE Reactive Power control capability provides significant benefits for systems with substantial dynamic reactive power requirements, including WPPs that are very large, are physically remote with electrically weak connections to the grid, or are located in areas with heavy and variable loads.

GE Energy's wind turbines that are equipped with WindFREE Reactive Power control can provide smooth, fast voltage regulation by delivering controlled reactive power even when the wind turbines are not generating active power. WPPs offering this type of control will provide effective grid reinforcements through continuous voltage regulation—a benefit not possible with conventional thermal or hydropower generation. The results of the WindFREE Reactive Power control feature test at the Tule WPP on a single GE 2.3-MW WTG are shown in Figure 37. The test was conducted when the turbine's active power production was at zero, but it displayed the capability to accurately control the reactive power in accordance to a set point.

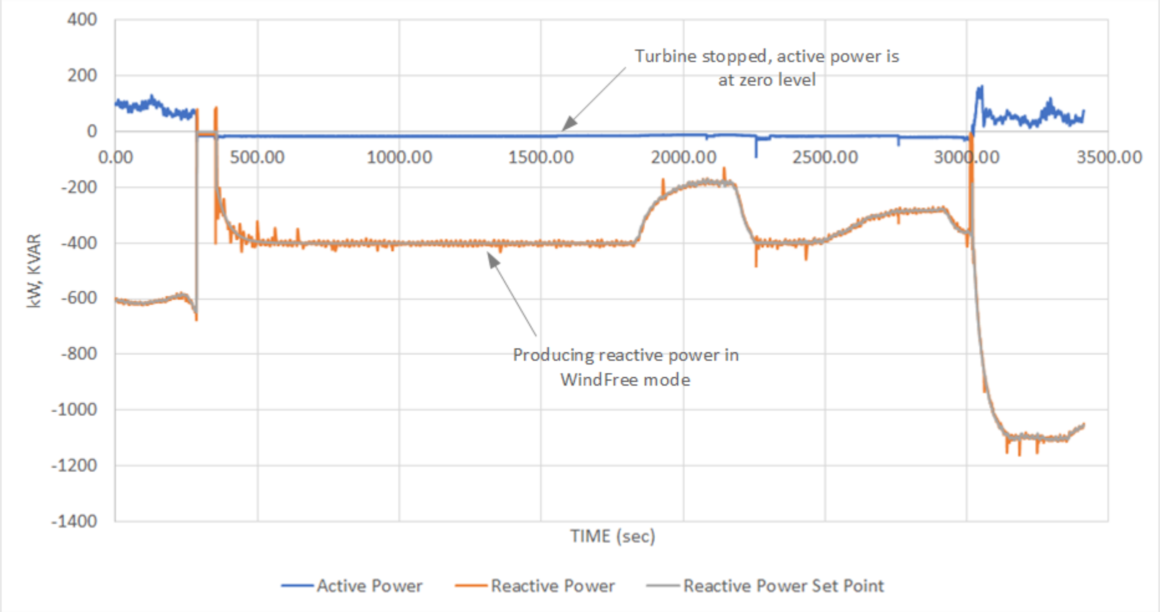

Figure 37. Reactive power control in WindFREE mode

Figure 38 shows the reactive power measured at the turbine terminals.

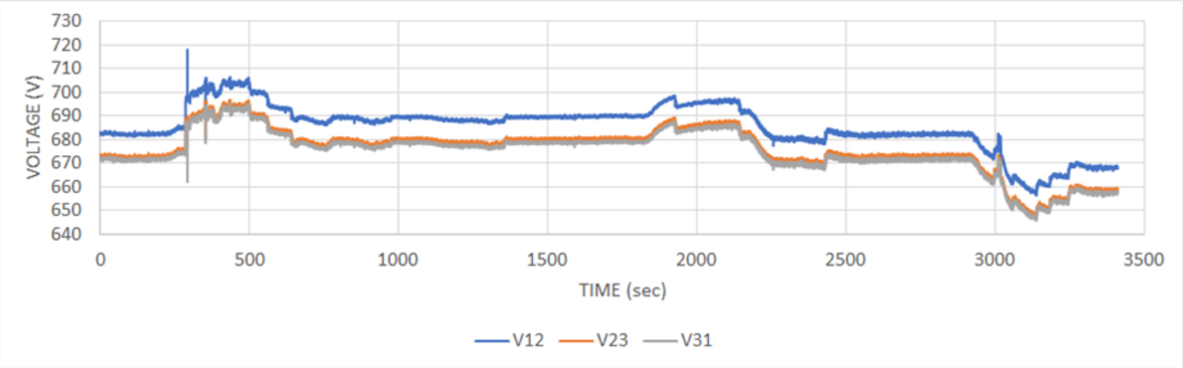

Figure 38. Turbine 690-V bus voltage in WindFREE mode

The ability of the Tule WPP to control the voltage at the 138-kV tie-line was demonstrated during the voltage control tests. The results of such tests are shown in Figure 39 when the plant was regulating the voltage in a tie-line based on set points commanded to GE's WindCONTROL. The active power production of the plant was approximately 70 MW during this test, as shown in Figure 40. The reactive power production at the plant POI changes in accordance with the voltage set points. As shown, the level of POI reactive power is well within the limits of the available reactive power calculated by the WindCONTROL.

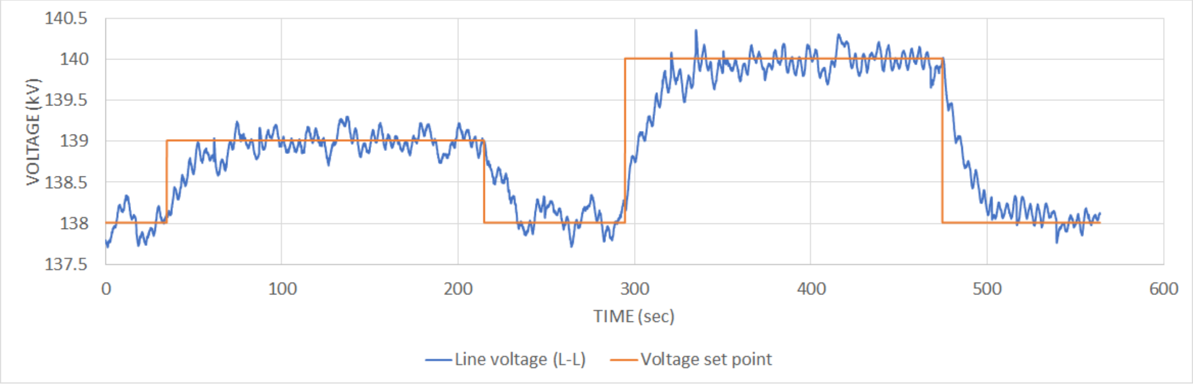

Figure 39. Voltage control test

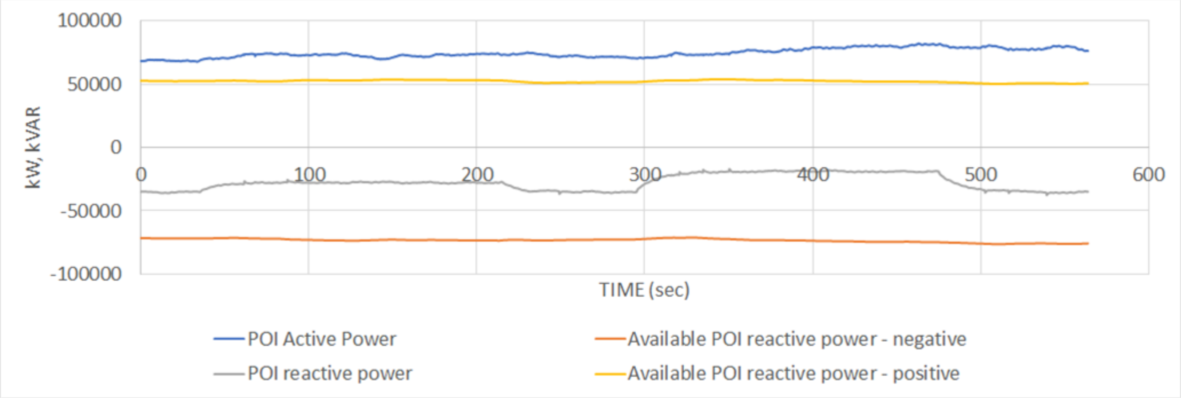

Figure 40. Active and reactive power during the voltage control test

9. Conclusions and Future Plans

The objective of this project was to demonstrate the ability of advanced controls of a 131.1-MW utility-scale WPP within CAISO's footprint to provide various types of active and reactive power controls for ancillary services. Active Power Control (APC) capabilities for inverter-connected plants, including wind plants, have been acknowledged and available for several years.

The AGC tests demonstrated the plant's ability to follow CAISO's 4-second AGC dispatch signals. For the AGC test, the plant was curtailed by 20 MW from its available peak power to have the maneuverability to follow CAISO's AGC signals. During these tests, fast and accurate AGC performance was demonstrated at different wind conditions.

For the frequency response tests, the plant was also operating in a curtailed mode to have enough headroom to increase its output in response to the frequency decline outside of a defined deadband. Headroom is achieved by sending a curtailment command to the plant PPC. The plant demonstrated fast and accurate frequency response performance for different droop settings (5% and 4% droop and 36 mHz and 16 mHz deadbands) under various wind conditions for both under- and over-frequency events.

The plant also demonstrated the ability to operate in voltage regulation mode and power factor control modes. The plant can operate in only one of the three modes at a time, with seamless transition from one mode to another. The plant controller was able to maintain the specified voltage set points at the POI by regulating the reactive power produced or absorbed by the wind inverters. Also, the plant's ability to produce or absorb reactive power at nearly zero megawatt production (STATCOM mode) was demonstrated.

9.1 General Conclusions

General conclusions include the following:

- Improvements in smart inverter technology combined with advanced plant controls allow inverter-based resources to provide regulation, voltage support, and frequency response during various mode of operation.

- Wind resources with these advanced grid-friendly capabilities have unique operating characteristics that can enhance system reliability by providing:
    - Essential reliability services during periods of oversupply
    - Voltage support when the plant's output is at zero
    - Fast frequency response (within the inertia response time frame)
    - Frequency response for low- as well as high- frequency events.

- Variable energy resources with the right operating characteristics are necessary to decarbonize the grid.
- Accurate estimation of available peak power capability is important for the precision of AGC control. It makes sense to include specifications for such available peak power estimations in future interconnection requirements and resource performance verification procedures.
- System-level modeling exercises will be needed to determine the exact parameters of each control feature to maximize the reliability benefits to CAISO or any other system operator that will be using such controls in its operations.
- All hardware components enabling WPPs to provide a full suite of grid-friendly controls already exist in many utility-scale WPPs. It is mainly a matter of activating these controls and/or implementing communications upgrades to fully enable them. Issues to be addressed in the process include communications protocol compatibility and proper scaling for set point signals. Although these are not significant barriers, dialogue and interaction between the plant operators and the system operators is an important component of implementing active power control capabilities. Modifying programming logic might be necessary at multiple places in the chain of communications.
- Fine-tuning the PPC to achieve rapid and precise response might be a necessary step in many WPPs. It might be easier with newer equipment because of the faster response times of newer inverters and controller systems.
- Many utility-scale WPPs are already capable of receiving curtailment signals from grid operators; each plant is different, but it is expected that the transition to AGC operation mode will be relatively simple with modifications made only to a PPC and interface software.
- Fast response by wind inverters coupled with plant-level controls make it possible to develop other advanced controls, such as STATCOM functionality, power oscillation damping controls, subsynchronous control oscillation damping and mitigation, active filter operation mode by wind inverters, and other features.

9.2 Future Plans

Future plans by the project team include:

- Identify potential barriers to providing essential reliability services to make them operationally feasible.
- Explore economic and/or contractual incentives to maximize production to provide reliability services.
- Identify necessary steps to unlock opportunities to use reliability services from renewable resources by:
    1) Assessing and quantifying the fleet's capability to provide reliability services
    2) Considering how renewable resources already dispatched or curtailed down can provide upward regulation and frequency response
    3) Identifying what tariff changes are necessary to remove barriers and allow variable energy resources to provide reliability services
    4) Exploring ways to allow inverter-based resources and associated control systems to be used to enhance reliability and response to frequency events
    5) Exploring further opportunities for inverter-based resources to participate in the various markets for energy and ancillary services, including the promise of pairing with storage to develop dispatchable renewable resources, or generation that follows market signals.
- Further modify control algorithms and fine-tune control parameters for improved performance of the demonstrated services.
- Demonstrate true wind-STATCOM functionality during all hours of operation.
- Demonstrate ancillary services by several WPPs within CAISO's footprint to understand the impacts of wind resource geographic diversity on aggregate response by wind generation on various types of ancillary services.
- The project team considered testing the capability of the Tule WPP to provide synthetic inertia; however, this test was not completed because of the cost and labor required to upgrade controls in all 57 turbines at the plant. In addition, the project team did not view the inertial response from wind power as an essential service at the present time because the Western Interconnection does not anticipate an inertia deficiency in the near future. When this test is completed in the future, an addendum to this report will be published.

10. References

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11. Appendix: Test Plan

1. Objective

The goal of this study was to perform multiple tests and document the performance of a utility-scale wind facility (Avangrid Renewables' Tule Wind Farm, located near San Diego) in a commercially operational setting. The plant currently has a maximum capacity of 131.1 MW and participates in the California Independent System Operator (CAISO) energy market. The plant uses General Electric (GE) 1.5-MW Type 3 wind turbine generators (WTGs) (doubly-fed induction generator electrical topology), and it is equipped with a GE WindCONTROL system that communicates with each WTG located in the wind power plant (WPP). This is a closed-loop control system that reads the actual WPP electrical parameters (voltage, reactive power, and megawatt output) at the point of interconnection (POI) (or location of the current transformers and potential transformers used by the WindCONTROL system) and adjusts the individual WTG's parameters to affect the overall WPP parameters toward its set points. CAISO proposes undertaking the following tests to demonstrate the resource's capability to provide:

a. Regulation up and regulation down
b. Voltage regulation control
c. Active power control
d. Frequency response
e. Inertial response (if possible).

The specifics of these tests are covered in this test plan. Also, for these tests, CAISO requested that Avangrid Renewables acknowledge and agree to the following conditions:

1. The additional tests will not involve operating equipment beyond its design limitations as specified by Avangrid Renewables.
2. The tests will in no way change any operational requirements of the facility already established in the interconnection agreement.
3. Completion of the additional tests will not certify the resource for CAISO participation in CAISO's ancillary markets.
4. Meter settlement during this commissioning and additional tests will follow standard procedures under which metered performance data are settled as uninstructed imbalance energy.
5. The additional tests will not affect the obligation of any existing contractual obligations between the parties.

CAISO is responsible for ensuring that there enough ancillary services are available to maintain the reliability of the grid under its jurisdiction. Modern utility-scale WPPs consist of multiple power electronic inverters and can contribute to grid stability and reliability through sophisticated grid-friendly controls. The findings of this test will provide valuable information to CAISO concerning the ability of a utility-scale wind resource to provide ancillary services, enhance system reliability, and participate in future ancillary service markets such as traditional generators. All tests will be done in a manner to minimize curtailment to the plant below its current commercial Pmax (for available wind speed at the time) and operate within its design capabilities. Curtailment details and actual test times will be worked out prior to the tests.

The project team will consist of experts from CAISO, Avengrid Renewables, the National Renewable Energy Laboratory (NREL), and GE and will develop the demonstration concept and test plan to show how various types of active and reactive power controls can leverage a wind resource from being a simple intermittent energy resource to a resource that can provide a wide range of ancillary services. If wind-generated power can offer a supportive product that benefits the power system and is economic for WPP owners and customers, this functionality should be recognized and encouraged.

From a control perspective, the ancillary services by wind power can be divided into two main categories: services based on turbine-level controls and services based on plant-level controls. Turbine level controls include inertial response, fault ride-through, and WindFREE voltage control.

The plant-level controls are based on the GE WindCONTROL plant controller system, which provides aggregate response for active power control set point operation, reserve margin, ramp control, droop control (both symmetric and nonsymmetric), and reactive power and power factor control.

2. Regulation Up and Regulation Down (Automatic Generation Control Response)

This test will demonstrate the plant's ability to follow CAISO's automatic generation control (AGC) dispatch signals. The purpose of AGC is to enable the power plant to follow the active power set point dispatched by CAISO at the end of every 4-second time interval. Normally, CAISO measures the accuracy of a resource's response to energy management system signals during 15-minute intervals by calculating the ratio between the sum of the total 4-second set point deviations and the sum of the AGC set points.

Expectation

During the test, CAISO will monitor the delayed response time of the plant (i.e., the time between the resource receiving a control signal indicating a change in set point and the instant the resource's megawatt output changes). CAISO will also monitor the accuracy of the plant's response to the regulation set point changes. The data from this test will be used by CAISO in future resource-specific expected mileage for the purpose of awarding regulation-up and regulation-down capacity.

Curtailment

It is expected that the plant will be curtailed by 20 MW for approximately 20 minutes.

3. *Voltage Regulation Control*

CAISO will test the plant in the voltage regulation mode, whereby the controller maintains a scheduled voltage at the terminal of the generator step-up transformer by regulating the reactive power produced by the inverters. The voltage regulation system is based on the reactive capabilities of the inverters using a closed-loop control system similar to automatic voltage regulators in conventional generators.

The reactive power capability will be tested to show:

> The Federal Energy Regulatory Commission's (FERC's) proposed reactive capability (Order 827[4]), which requires all newly interconnecting nonsynchronous generators to design their generating facilities to meet the reactive power requirements at all levels of real power output. (See the V-shaped capability curve in Figure 1).

Objective

The primary objective of this test is to demonstrate the capability of the plant to operate in voltage regulation mode within 0.95 leading/lagging power factor range. The plant controller maintains the specified voltage set point at the high side of the generator step-up bank by regulating the reactive power produced by the inverters.

Test Procedure

CAISO will test the plant at three different real power output levels: (1) at maximum or close to maximum production, (2) at approximately 50% of its maximum capability, and (3) when the plant is close to zero production. CAISO will test the plant's reactive power capability to absorb and produce reactive power in accordance with Figure 1.

- The plant will first be tested at its maximum real power output for a given wind speed. At maximum real power output, a low-voltage schedule will be fed to the plant to demonstrate it can produce approximately 33% of real output as dynamic reactive. Similarly, at maximum real power output, a high-voltage schedule will be fed to the plant to demonstrate it can absorb approximately 33% of its real power output as reactive output.
- At approximately 50% of the resource maximum capability, the plant must demonstrate that it can produce and absorb approximately 33% of its real power output as dynamic reactive output.
- As the plant production approaches 10 MW, the plant must demonstrate that it can produce and absorb approximately 33% (3 MVAR) of its real power output as dynamic reactive output.
- An additional test to demonstrate the plant's reactive capability at zero output will also be done. If successful, this test will demonstrate the capability of the plant to provide reactive support at zero megawatt output.

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[4] http://www.ferc.gov/whats-new/comm-meet/2016/061616/E-1.pdf

For this purpose, the plant turbine must be equipped with GE's WindFREE control feature.

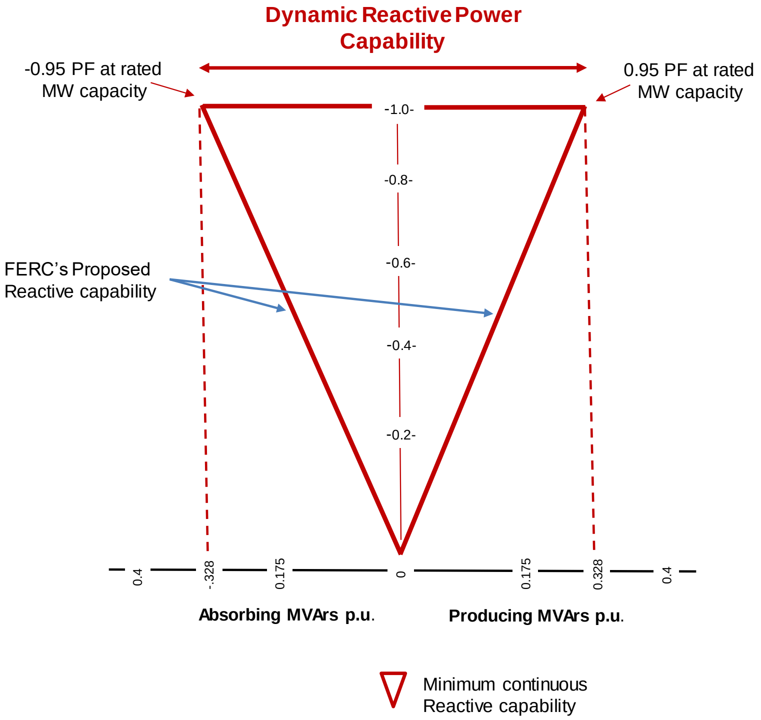

Figure 1. Reactive power capability at the POI

Note: The red vertical lines shown in Figure 1 represent the expected reactive capability of the asynchronous generating plant at the high side of the generator step-up bank. For example, a 100-MW plant would be required to provide approximately 33 MVAR of reactive support when operating at maximum output (i.e., 100 MW) and approximately 3.3 MVAR when operating at 10 MW and 0.3 MVAR when operating at 1 MW.

Expectation

The plant must demonstrate that its reactive capability follows FERC's proposed reactive capability as shown in Figure 1.

Curtailment

None

4. Active Power Control Capabilities

CAISO seeks to test the active power control capability to assess the plant's ability to control its output in specific increments by being able to mimic a specified ramp rate. The results of this test will be used to determine the plant's ability to provide ancillary services, such as spinning reserve and nonspinning reserve.

Objective

This objective of this test is to demonstrate that the plant can decrease output or increase output while maintaining a specific ramp rate.

Test Procedure

This test is similar to starting up and shutting down the plant in a coordinated and controllable manner. The test will be done at two different ramp rates.

- The plant will be instructed to reduce its output to three different set points (not to exceed 60 MW) at a predetermined ramp rate, as shown in Figure 2.
- The plant will then be instructed to ramp back up to full production following predefined set points at the predetermined ramp rate, as shown in Figure 2.
- Repeat this test using a different ramp rate

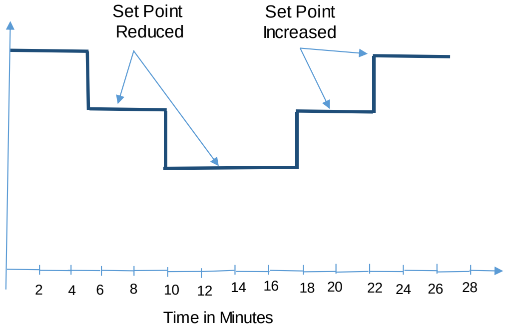

Figure 2. Increase/decrease output at a specified ramp rate

Expectation

The plant must demonstrate its capability to move from its current set point to a desired set point at a specified ramp rate.

Curtailment

It is expected that this test will require the plant to be curtailed for approximately 20 minutes.

5. Frequency Response

The frequency response capability will entail two separate tests: (1) a droop test and (2) a frequency response test. The definition of implemented frequency droop control for a WPP is the same as that for a conventional generator:

$$\frac{1}{Droop} = \frac{\Delta P/P_{rated}}{\Delta f/60Hz}$$

The plant rated power (131.1 MW) is used in this equation for the droop-setting calculation. The plant should adjust its power output in accordance with the droop curve with symmetric deadband, as shown in Figure 3. The upper limit of the droop curve is the available plant power based on the current level of wind speed.

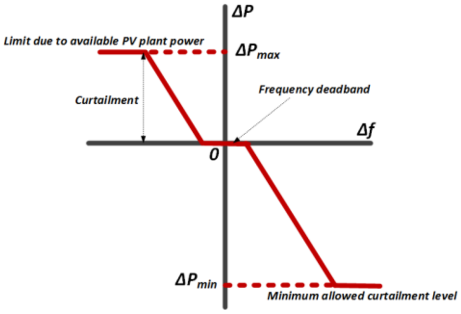

Figure 3. Frequency droop explained

Objective

The objective of this test is to demonstrate that the plant can provide a response in accordance with 5% and 4% droop settings through its governor-like control system. The plant will be instructed to operate below its maximum capability during both tests.

Test Procedure

For the first test, the plant will be instructed to operate at 20 MW below its maximum capability. This test will be done using a 5% and 4% droop and a deadband of ± 36 mHz and ± 16 mHz.

- The independent system operator will test the frequency droop capability of the plant by using an actual under-frequency event that occurred in the Western Interconnection. The under-frequency event data set (approximately 10 minutes of data) will be fed into the plant’s controller, and the plant’s response will then be monitored.

- The frequency droop capability will be demonstrated using one actual high-frequency time-series data set provided by NREL. Examples of under- and over- frequency event time series measured by NREL are shown in Figure 4 and Figure 5, respectively.

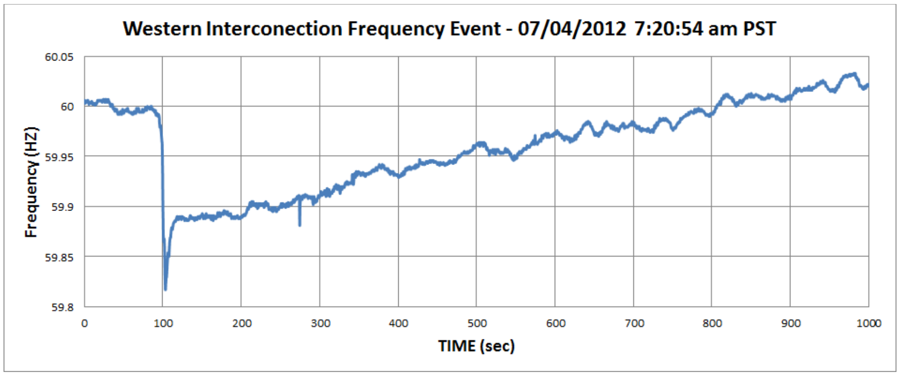

Figure 4. Example under-frequency event

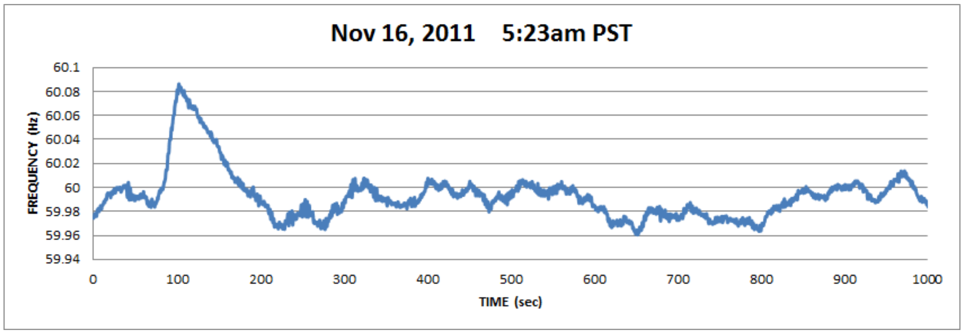

Figure 5. Example over-frequency event

- The frequency event time-series data will be used by the power plant controller to trigger the droop response by the plant.

- This test will be repeated with the plant at 20 MW less than its maximum capability. This test will be done using a 3% droop and a deadband of ± 36 mHz.

Expectation

Through the action of the governor-like control system, the plant must respond automatically within 1 second in proportion to frequency deviations outside the deadband.

Curtailment

It is expected that for the low-frequency tests, the plant will be curtailed for approximately 20 minutes.

Objective

The objective of this test is to demonstrate that the plant can provide fast frequency response and frequency response consistent with the North American Electric Reliability Corporation's BAL-003-1 standard.

The plant will be instructed to operate 20 MW below its maximum capability before applying a step change of rapid frequency decline. An actual frequency event (approximately 10 minutes) will be fed into the plant's controller, and the plant's response will be monitored. This test might require tuning a delay in response to ensure that the frequency response occurs within 20–52 seconds following the step change in frequency.

Expectation

Through the action of the governor-like control system, the plant must respond automatically in proportion to frequency deviations.

Curtailment

It is expected that this test will be curtailed for approximately 20 minutes.