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USING RENEWABLES TO OPERATE A LOW-CARBON GRID:

Demonstration of Advanced Reliability Services from a Utility-Scale Solar PV Plant

California ISO

First Solar

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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List of Acronyms

ACE	Area Control Error
AGC	Automatic Generation Control
APC	active power control
BA	Balancing Authority
CAISO	California Independent System Operator
FFR	fast frequency response
NREL	National Renewable Energy Laboratory
PFR	primary frequency response
POI	point of interconnection
PPC	power plant controller
PV	photovoltaic
ROCOF	rate of change of frequency
SCADA	Supervisory Control and Data Acquisition

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Abstract

The California Independent System Operator (CAISO), First Solar, and National Renewable Energy Laboratory (NREL), conducted a demonstration project on a large utility-scale photovoltaic (PV) plant in the CAISO's balancing area to test its ability to provide important ancillary services to the grid. With an increasing share of solar and wind generated energy, traditional power generation resources equipped with automatic governor control and automatic voltage regulation controls, specifically fossil thermal, are being displaced. Deployment of utility-scale, grid-friendly PV power plants that incorporate advanced capabilities to support grid stability and reliability is essential for the large-scale integration of PV generation into the electric power grid, among other technical requirements. A typical photovoltaic (PV) power plant consists of multiple power electronic inverters and can contribute to grid stability and reliability through sophisticated "grid-friendly" controls. It may in this way mitigate the impact of its variability on the grid, and contribute to important system requirements more like traditional generators.

In August 2016, testing was conducted on one of the First Solar's 300-megawatt plant, and a large amount of test data was produced and analyzed that demonstrates the capability of PV power plants to provide various types of new grid-friendly controls. This data showed how the development of advanced power controls can leverage PV's value from being simply an intermittent energy resource to providing services that range from spinning reserves, load following, voltage support, ramping, frequency response, variability smoothing and frequency regulation to power quality. Specifically, the tests conducted included various forms of active power controls such as automatic generation control (AGC) and frequency regulation, droop response, and reactive power/voltage/power factor controls.

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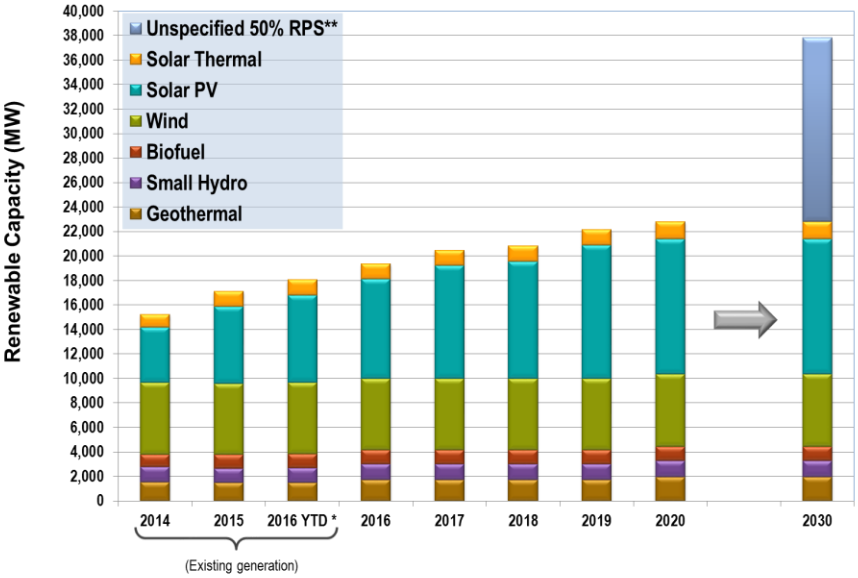
1. Introduction

As of the end of 2015, the U.S. had 25 gigawatts (GW) of installed photovoltaic capacity with an additional 1.8 GW of concentrated solar power [1]. In the 12 months ending June 2016, utility-scale solar power generated 31.7 terawatt-hours (TWh), 0.78% of the total U.S. electricity supply. During the same time period, total solar generation, including estimated distributed solar photovoltaic generation, was 46.3 TWh, 1.14 % of the total U.S. electricity load [2]. In 2015, 30 percent of all new electricity generation capacity in the country came from solar [1].

Renewable energy in the U.S. accounted for 13.44 percent of the domestically produced electricity in 2015 [3]. California is a leading state for integrating renewable resources, with about 29 percent of California's electricity provided from RPS eligible renewable sources (including small hydropower) [4]. In addition, California is also leading the way in climate change policies intended to reduce emissions from all sectors, including the electricity sector by 40 percent of 1990 levels by 2030 and 80 percent of 1990 levels by 2050. If California is to achieve these goals while maintaining grid reliability, all resources, including renewables, must be leveraged to provide essential reliability services.

Rapid penetration of variable renewable generation into the power grid is already changing the ways system operators are managing the grid. Higher levels of variable generation are creating some real-time reliability and operational changes for system operators. For example, the CAISO is trying to adapt to rapid increases in its solar PV generation during sunrise and rapid loss in solar production during sunset.

The CAISO currently has over 9,000 MW of transmission connected solar resources within its operational footprint. To meet its 33 percent RPS by 2020, the CAISO is expecting an additional 4,000 to 5,000 MW of solar. Beyond 2020, to meet a 50 percent RPS, the CAISO is expecting an additional 15,000 MW of renewable resources, and a significant portion of this is anticipated to be transmission connected solar PV due to the expected reduction in price of solar panels (Figure 1). Thus, the capability of solar PV resources to provide essential reliability services necessary to reliably achieve a low-carbon grid.



*All online resources that are not in test mode are included in the 2016 YTD amounts, including those yet to achieve full commercial operation.
**Approximate

Figure 1. CAISO's Expected Renewable Build-out to meet 50% RPS

In addition, the CAISO has seen a significant increase in rooftop solar PV installation (Figure 2). Currently there is in excess of 5,000 MW of rooftop solar PV within the CAISO's footprint, and that number is expected to exceed 9,000 MW by 2020. Rooftop solar PV does not count towards RPS, but does have an impact on grid operation especially during sunrise and sunset.

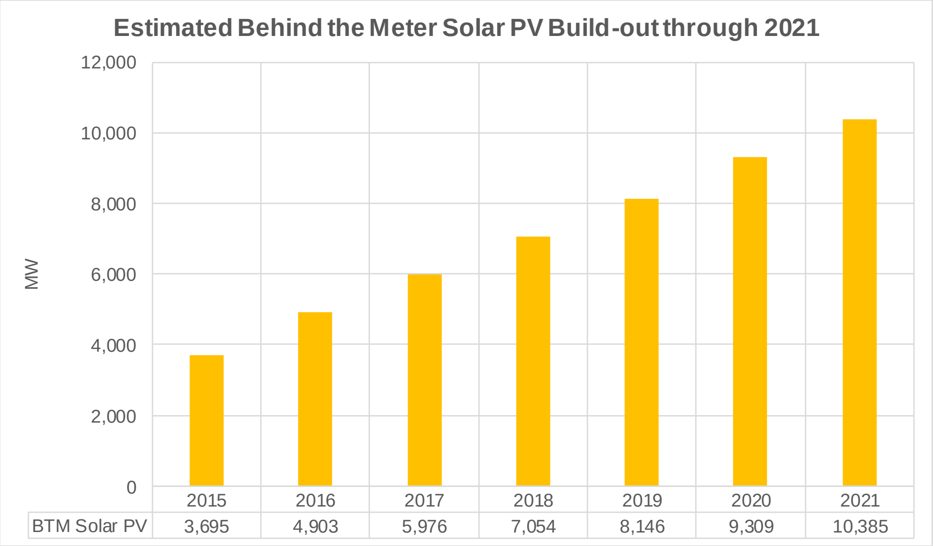


Figure 2. CAISO's expected build-out of Rooftop Solar PV

High levels of solar generation during mid-day hours are already contributing to oversupply, especially on light load days when renewable production is high. Therefore, it is during these conditions that opportunity is created if renewable resources could provide essential reliability services that have traditionally been provided by conventional resources. Sharp changes in the real-time ramping needs are also happening during afternoon and evening hours. This is especially evident during the spring and fall months when loads are relatively light and hourly penetrations of renewable generation is high. As shown in its Duck Chart, Figure 3, the CAISO depicted these integration changes and opportunities for a typical spring day where significant drop in its mid-day net load as PV shared is increased in the system. These changes and opportunities to leverage the capability of these new resources are growing at a faster rate than previously expected, and during certain days in spring 2016 the CAISO minimum net load was already below the predicted 2020 level.

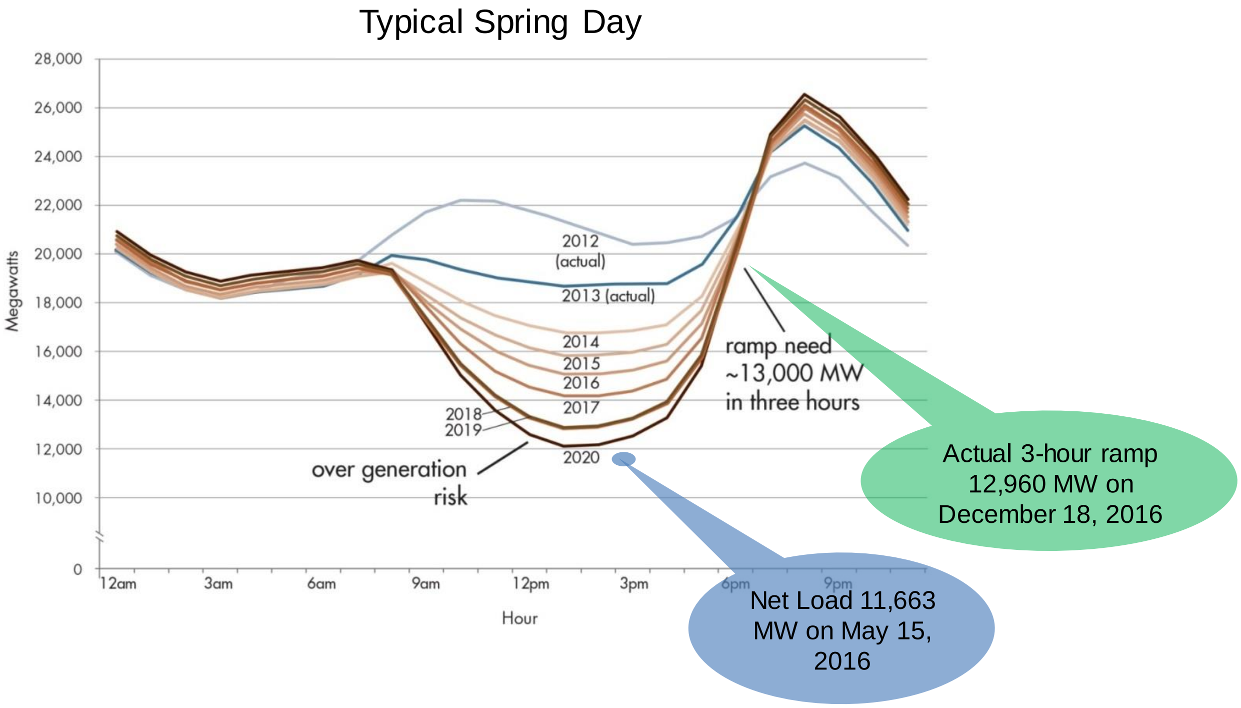


Figure 3. CAISO duck chart (source: CAISO)

Because of low net loads the risk of oversupply increases, so significant levels of renewables curtailment took place during certain days of the spring of 2016. An example of such a curtailment period is shown in Figure 4. During certain daytime hours on April 24, 2016, over 2 GW of renewable generation had to be curtailed to maintain reliable operation of the system. With increased frequency of curtailment, more opportunity is created if the industry can tap into the controllability of the renewable resources, and thus expand the carbon-free resources for such services.

Advanced inverter functions, along with the design and operation of projects, can help address the grid stability problems during such periods. A typical modern utility-scale PV power plant is a complex system of large PV arrays and multiple power electronic inverters, and it can contribute to mitigating the impacts on grid stability and reliability through sophisticated automatic “grid-friendly” controls. Many of the PV control capabilities that were demonstrated in this project have already generally been proven to be technically feasible, and a few areas throughout the world have already started to request or require PV power plants to provide some of them. However, in the United States, utility-scale PV plants are rarely recognized as having these capabilities and typically are not used by utilities or system operators for electrical grid services.

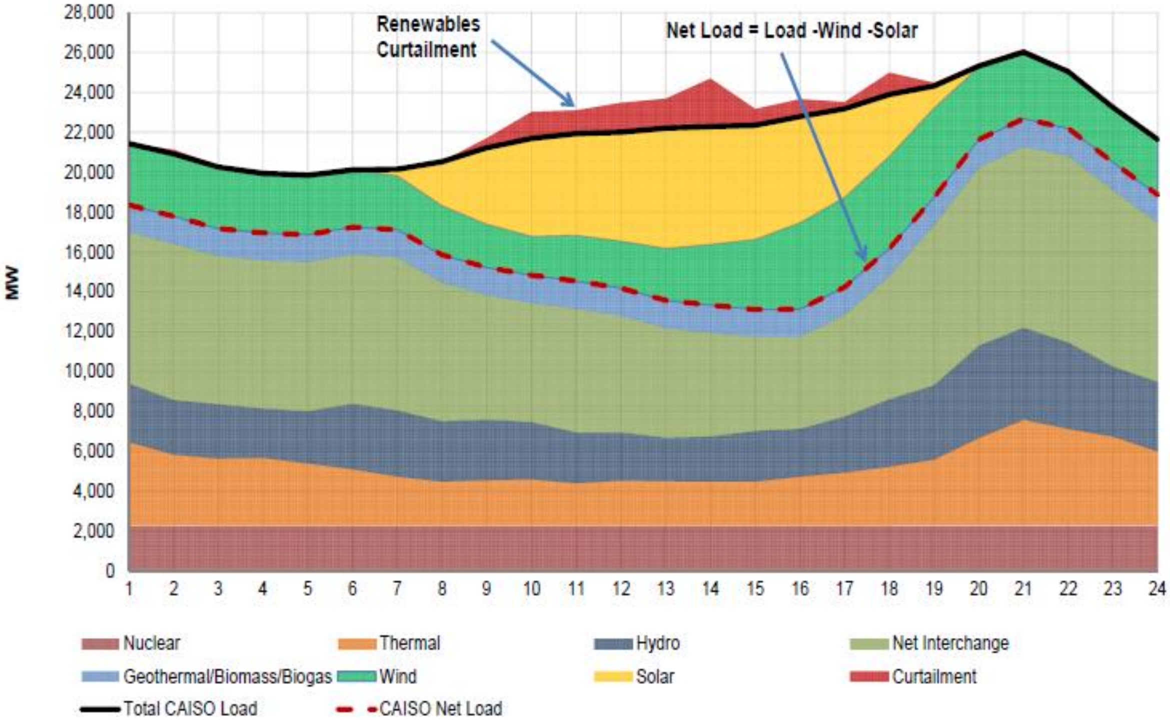


Figure 4. CAISO generation breakdown for April 24, 2016 (source: CAISO)

The CAISO is continually adapting its operational practices and market mechanisms to make integration of fast growing variable renewable generation both reliable and economically viable. This new reality leads to a growing need by the CAISO and other ISOs for:

- Better coordination between day-ahead and real-time markets
- Increased flexibility in the form of fast ramping capacity
- Better utilization of ancillary service capabilities by variable renewable generation
- Deepened regional coordination
- Implementation of new market mechanisms incentivizing renewables participation 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 the 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. The CAISO procures incremental ancillary services in the real-time market processes to replace unavailable ancillary service or to meet additional ancillary service requirements. A detailed description of the ancillary service market design, which was implemented in 2009, is provided in DMM's 2010 annual report [5].

From February 20 through June 9, 2016, the CAISO increased the requirements to a minimum of 600 MW for regulation up and regulation down in both the day-ahead and real-time markets. Average prices for these two ancillary services increased immediately following the change in requirements in February and reverted back to lower levels again in June (Figure 5). Regulation procurement costs continued to average over $400,000 per day when the requirements were higher and fell to $80,000 per day when the requirements were lowered beginning June 10.

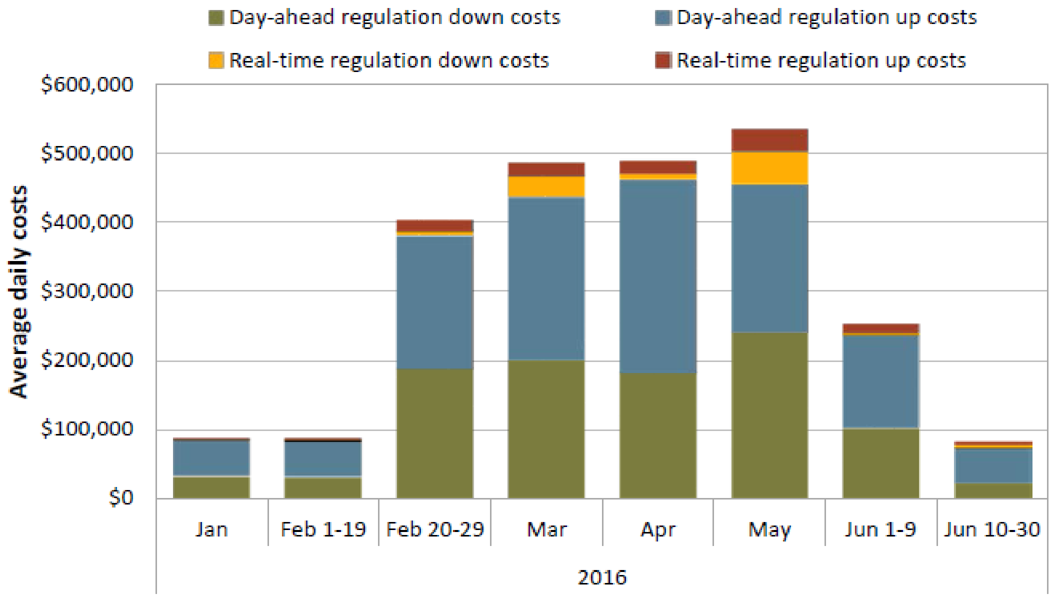


Figure 5. CAISO average daily regulation procurement costs during Jan-June, 2016 (source: CAISO)

In 2012, the CAISO implemented standards for importing of regulation [7]. These standards implemented CAISO tariff provisions relating to imports of regulation services, either bid or self-provided, by Scheduling Coordinators with system resources located outside the CAISO balancing authority area. In additional to imported regulation services, regulation provided by PV power plants within the CAISO footprint can become an additional stability tool at CAISO's disposal.

FERC Orders 755 and 784 enabled enhanced compensation for the ancillary services provided by fast-response resources such as energy storage. There are evolving market mechanism in many U.S. ISOs for integrating fast-responsive resources in their markets. CAISO is working on a new market design in which aggregated distributed resources (roof-top PV, behind-the-meter batteries, electric vehicles, fast demand response) can bid in its market. ERCOT and NYISO are also working on similar ancillary service markets by utility-scale and distributed generation.

In 2012, the North American Electric Reliability Corporation's (NERC) Integration of Variable Generation Task Force made several recommendations of requirements for variable generators (including solar) to provide their share of grid support, including active power control capabilities [7], [8]. These recommendations address grid requirements such as voltage control and regulation, voltage and frequency-fault ride-through, reactive and real power control, and frequency response criteria in the context of the technical characteristics and physical capabilities of variable generation equipment:

- Active power control (APC) capabilities include:
    - Ramp-rate limiting controls
    - Active power response to bulk power system contingencies
        - Inertial response
        - Primary frequency response (PFR)
        - Secondary frequency response, or participation in automatic generation control (AGC)
        - Ability to follow security-constrained economic dispatch (SCED) set points that are sent every 5 minutes through its real-time economic dispatch market software.
- Performance during and after disturbances
    - Fault ride-through
    - Short-circuit current contribution
- Voltage, reactive, power factor control and regulation (both dynamic and steady state)

In 2015, NERC task force on Essential Reliability Services published a report exploring important directional measures to help the energy sector understand and prepare for the increased deployment of variable renewable generation [10]. According to this report, in order to maintain an adequate level of reliability through this transition, generation resources need to provide sufficient voltage control, frequency support, and ramping capability—essential components of a reliable bulk power system.

The California state legislature passed Senate Bill 350 in fall 2015, which requires all utilities in the state to produce 50 percent of their electricity sales from renewable sources, with the objective of reducing carbon emission. To reach that 50-percent RPS goal, California operators will need to find additional ways to balance generation and load to manage the variability of increased renewable generation in order to maintain grid reliability. In this context, the curtailment of renewables can be viewed as a resource, not only a problem. Because wind and solar generation can be ramped up and down, curtailment can become a helpful resource to relieve oversupply, provide frequency regulation, and ramping services. In combination with the 1.3 GW California energy storage mandate, ancillary services provided by renewables can enhance system flexibility and reliability, and reduce needs in spinning reserves by conventional power plants. Thus, unleashing these capabilities from the renewable resources helps achieving the broader objective of a resilient, reliable low-carbon grid.

Currently, only few grid operators in the U.S. are using the renewables curtailment as a resource. For example, the Public Service Company of Colorado (PSCO) has means to control its wind generation to provide both up and down regulation reserves (PSCO has had periods of 60-percent wind power generation in its system). PSCO is able to use wind reserves as an ancillary service for frequency regulation by integrating the wind power plants in their footprint to AGC. Similar services can be provided by curtailed PV power plants in California, however regulatory, market, and operational issues need to be resolved for this to become possible.

The project team consisting of experts from CAISO, First Solar and NREL has developed the demonstration concept and test plan to show how various types of active and reactive power controls can leverage PV generation's value from being a simple intermittent energy resource to a resource providing a wide range of ancillary services. This demonstration on an actual utility-scale operational PV power plant and consecutive dissemination of obtained results, the team will provide valuable real test data to all stakeholders in California and nationwide. If PV-generated power can offer a supportive product that benefits the power system and is economic for PV power plant owners and customers, this functionality should be recognized and encouraged.

With this project's approach to holistic demonstration and dissemination plans, the team sought to close some gaps in perspectives that exist between various stakeholder groups in California and other locations in the U.S. by providing real test data from an actual large utility-scale operational PV power plant to all stakeholders.

Some elements of this project were built upon the pioneering work done by NREL, First Solar and AES in 2015 utilizing 20 MW PV power plants in West Texas and Puerto Rico [11]. The current CAISO-First Solar-NREL project is aimed at breaking down new barriers to utilization of ancillary services by PV generation in terms of both plant capacity (300 MW) and system level impacts.

Prior to testing, the team developed a test plan that was coordinated with technical experts of First Solar. The test plan is shown in Appendix A of this report). The description and results for following tests conducted by the team will be presented in the following sections. Following is a list of conducted tests:

1. CAISO-NREL-First Solar custom-developed test scenarios (conducted on August 24, 2016)
    a. Regulation up and down, or AGC tests during sunrise, middle of the day, and sunset
    b. Frequency response tests with 3% and 5% droop setting for over and under-frequency conditions
    c. Curtailment and active power control tests to verify plant performance to decrease or increase its output while maintaining specific ramp rates
    d. Voltage and reactive power control tests

    e. Voltage control at near zero active power levels (night time control)

2. More standardized First Solar's plant control system commissioning tests (conducted on August 23, 2016)

    a. Automatic manual control of inverters (individual, blocks of inverters, whole plant)

    b. Active power curtailment control, generation failure and restoration control, frequency controls validation

    c. Automatic voltage regulation at high and low power generation

    d. Power factor control

    e. Voltage limit control

    f. VAR control

2. PV Plant Description

First Solar has constructed a 300-MWac PV power plant in the CAISO footprint. The aerial photo of the plant using First Solar advanced thin film Cadmium-Telluride (Cd-Te) PV modules is shown in Figure 6. The plant is tied to 230 kV transmission lines via two 170 MVA transformers (34.5/230 kV). The 34.5 KV side of each transformer is connected to the plant's MV collector system with four blocks each rated at 40 MVA. Individual PV inverter units, each rated at 4 MVA, are operating at 480 VAC and connected to 34.5 kV collector system via pad-mount transformers. Switched capacitor banks are connected to both 34.5 kV buses to meet the large generator interconnection agreement (LGIA) power factor requirements. Two phasor measurement units (PMU) were set to collect data at 230 kV sides of both plant transformers.

Figure 6. Aerial photo of 300 MW PV power plant (source: First Solar)

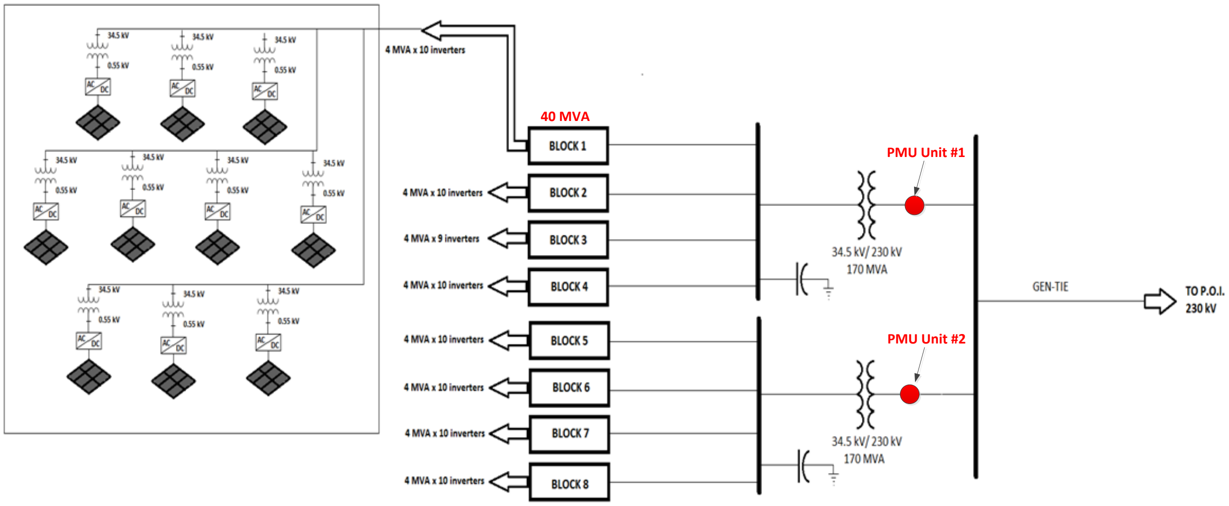


Figure 7. Electrical diagram of 300 MW PV plant (source: First Solar)

A key component of this tested grid-friendly solar PV power plant is the plant-level controller (PPC) developed by First Solar. It is designed to regulate real and reactive power output from the PV power plant so that it behaves as a single large generator. Although the plant is comprised of individual inverters, with each inverter performing its own energy production based on local solar array conditions, the function of the plant controller is to coordinate the power output to provide typical large power-plant features, such as APC and voltage regulation through reactive power regulation [12].

First Solar's PPC is capable of providing the following plant-level control functions:

- Dynamic voltage and/or power factor regulation, and closed loop VAR control of the solar power plant at the point of interconnection (POI),
- Real power output curtailment of the solar power plant when required so that it does not exceed an operator-specified limit,
- Ramp-rate controls to ensure that the plant output does not ramp up or down faster than a specified ramp-rate limit, to the extent possible,
- Frequency control (governor-type response) to lower plant output in case of an over-frequency situation or increase plant output (if possible) in case of an under-frequency situation
- Start-up and shutdown control.

The PPC implements plant-level logic and closed-loop control schemes with real-time commands to the inverters to achieve fast and reliable regulation. It relies on the ability of the inverters to provide a rapid response to commands from the PPC. Typically, there is one controller per plant controlling the output at a single high-voltage bus (referred to as the POI). The commands to the PPC can be provided through the SCADA human-machine interface or even through other interface equipment, such as a substation remote terminal unit.

Figure 8 illustrates a general block diagram overview of the First Solar 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 the specified targets. It manages capacitor banks and/or reactor banks, if present. 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 POI [12].

A conceptual diagram of the plant control system architecture is shown in Figure 9. The plant operator can set an active power curtailment command to the controller. In this case, the controller calculates and distributes active power curtailment to individual inverters. In general, some types of inverters can be throttled back only to a certain specified level of active power and not any lower without causing the DC voltage to rise 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. It cannot, however, always accommodate rapid reductions in irradiance caused by cloud cover.

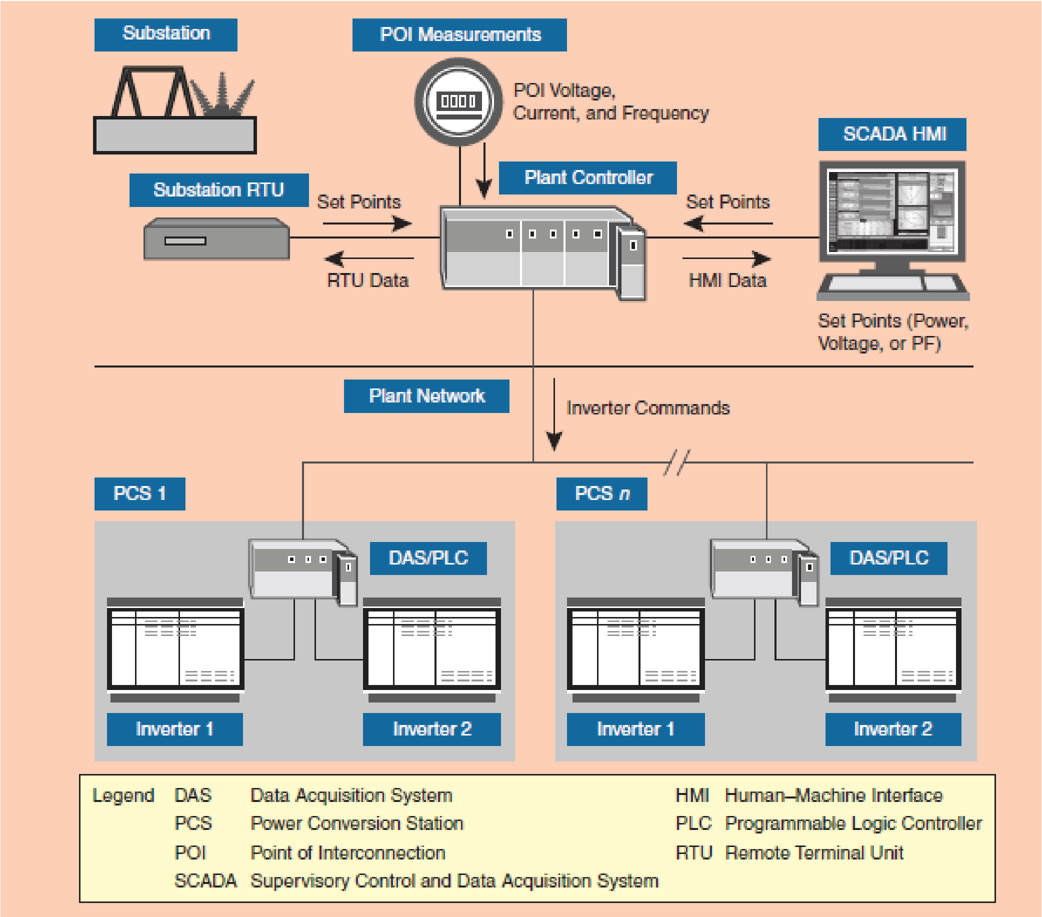


Figure 8. General diagram of First Solar PV power plant controls and interfaces, Image from First Solar

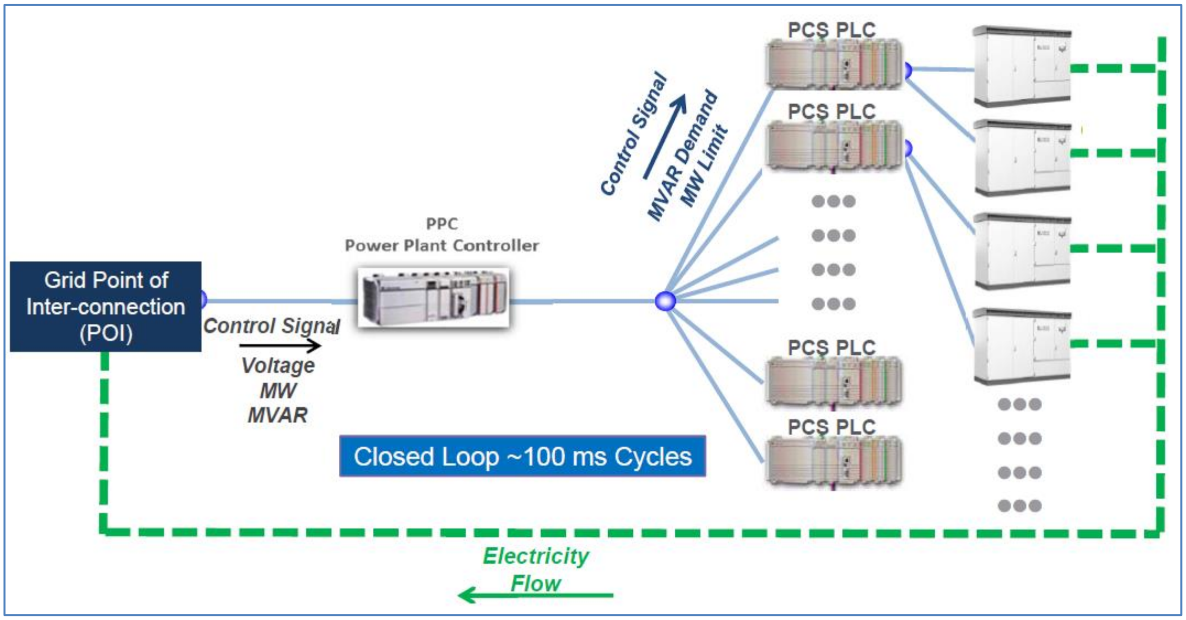


Figure 9. Diagram of a First Solar PV power plant control system architecture. Image from First Solar

The testing of the 300 MW plant within the CAISO's footprint was conducted remotely by the First Solar team from their operations center located in First Solar corporate offices in Tempe, AZ (Figure 10). As a NERC registered generator operator, the First Solar staff was capable of remotely supervising the ongoing testing activities at the 300 MW PV plant in California, tracking the plant performance and making changes to test set point and plant control parameters from this center in Arizona.

Figure 10. First Solar operations center in Tempe, AZ. Image from First Solar

3. AGC Participation Tests for First Solar's 300 MW PV Power Plant

3.1 Description and rationale for AGC Tests

The purpose of the AGC tests is to enable the power plant to follow the active power set points sent by the CAISO's AGC system. The set point signal is received by the remote terminal unit in the plant substation and then scaled and routed to the PPC in the same time frame. When in AGC mode, the PPC initially set the plant to operate at a power level that was 30 MW lower than the estimated available peak power in order to have headroom for following the up-regulation AGC signal (see hypothetical example in Figure 11). The lower boundary of AGC operation can be set at any level below available peak power, including full curtailment if necessary.

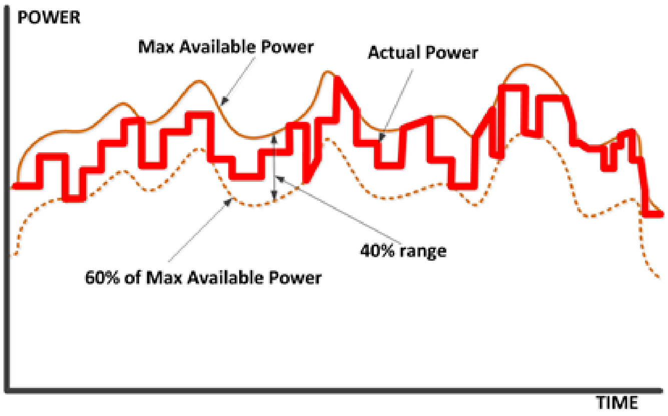


Figure 11. Concept of AGC following by PV power plant (e.g. with 40% headroom)

CAISO's AGC is normally set to send a direct MW set point signal to all participating units every four seconds. All ramp-rate settings in the PV power plant PPC were disabled during the AGC tests. AGC control logic for a balancing authority with interconnections (such as CIASO) is based on determining the:

- Area's total desired generation
- Base points 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 area, ACE is determined as:

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

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, but can be also 59.98 Hz or 60.02 Hz during manual time error correction), respectively; and I_{ME} and I_T are the meter error correction and time error correction factors, respectively (MW). The *ACE* value is then used by the AGC control logic to determine the total desired generation that will drive it to zero. The desired generation for each participating generating unit is split into two components: the base point and regulation. The base point for each generating unit is set at its economic dispatch point, and the system total regulation is calculated as the difference between the total desired generation and the sum of the base points for all AGC participating units. The total regulation for the whole system is allocated among all participating regulating units. The 300 MW plant under test is considered as a one plant-level generating unit, and individual inverter outputs are not considered by CAISO's operations. Various unit-specific parameters are used in its regulation allocation, such as ramp rates and operating limits. Figure 12 shows a general diagram of CAISO's AGC distributing set point signals to individual generating units. The raw ACE signal is filtered first, and then processed by PI filter that has proportional and integral control gains. The filtered ACE is then passed to AGC calculation and distribution module that generates ramp-limited AGC set points for individual participating units based on their participation factor, dispatch status, available headroom, unit physical characteristics, etc. as shown in Figure 12.

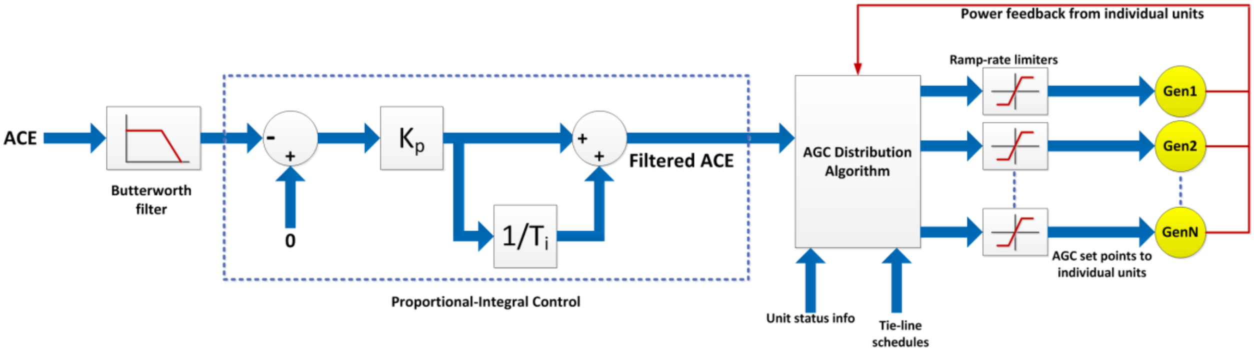


Figure 12. Simplified diagram of CAISO AGC system

AGC operates in conjunction with Supervisory Control and Data Acquisition (SCADA) systems [13]. SCADA gathers information on system frequency, generator outputs, and actual interchange between the system and adjacent systems. Using system frequency and net actual interchange, plus knowledge of net scheduled interchange, an AGC system determines the system's energy balancing needs in near-real-time. The CAISO SCADA system polls sequentially for electric system data, with a periodicity of four seconds. The degree of success of AGC in complying with balancing and frequency control is manifested in a Balancing Area's control performance compliance statistics and metrics defined by NERC control performance standards (CPS). In particular, CPS1 is a measure of balancing area's long-term frequency performance with control objective to bound excursions of 1-minute average frequency error over 12 months in the interconnection. CPS1 allows evaluating how well a balancing area's ACE performs in conjunction with the frequency error of the whole interconnection. CPS2 is a measure of balancing area's ACE over all 10-minute periods in a month with control objective to limit ACE variations and bound unscheduled power flows between balancing areas.

The NREC's Standards Committee approved the replacement of CPS2 with Balancing Authority ACE Limit (BAAL) in June 2005. BAAL is unique for each BA and provides dynamic limits for its ACE value limits as a function of its interconnection frequency. The objective of BAAL is to maintain the interconnection frequency within predefined limits. A field trial of BAAL began in the Eastern Interconnection in July 2005 and in the Western Interconnection in March 2010. Enforcement of BAAL began on July 1, 2016 [14]. Both CPS1 and BAAL scores are important metric for understanding the impacts of variable renewable generation on system frequency performance. NERC reliability standards require that a BA 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.

PV generation participation in CAISO's AGC is expected to maintain CPS above minimum NERC requirements and BAAL within predefined operating limits, and avoid degradation in reliability. AGC participation by faster and higher precision responsive generation is potentially more valuable because they allow applying controls at the exact moment in time and exact amount needed by the system. Faster AGC control is desirable since it facilitates more reliable compliance with the NERC operating standards at relatively lesser regulation capacity procurements [15]. Currently, the CAISO practices and markets do not provide a differentiation between faster and slower providers with the exception of some minimum ramping capabilities. The data produced by AGC testing of the 300 MW PV plant in California is intended to provide real field measured data to confirm the above-described benefits and facilitate transition to improved ancillary service markets that value and incentivize such superb performance by inverter-coupled renewable generation.

The AGC tests were conducted on August 24, 2016 at three different solar resource intensity timeframes during sunrise, middle of the day, and sunset (20 minutes at each condition). Historic 4-sec AGC signals that CIASO previously sent to another regulation certified resource of similar capacity were provided to the plan controller.

3.2 AGC Test Results

The AGC tests were conducted on August 24, 2016, and were intended to demonstrates the plant's ability to follow the CAISO's AGC dispatch signals during three different solar resource intensity timeframes (1) sunrise, (2) middle of the day [noon – 2 p.m.], and (3) sunset. The 300 MW PV plant under test was not connected to CAISO AGC system since such control option was not requested by the plant owner by the time of plant construction. Instead, historic CAISO ACE data was provided to the PPC for AGC performance testing. Each test was conducted using an actual four-second AGC signals that the CAISO has previously sent to a regulation certified resource of similar size. The historic AGC signal provided by the CAISO was scaled down to represent regulation range with 30 MW, or 10% of rated plant power (Figure 13). This signal is represented as ΔP_{AGC} in the equation below:

$$P_{command} = (P_{available} - 30MW) + \Delta P_{AGC} \qquad (2)$$

Where $P_{available}$ is the maximum available instantaneous power the plant can produce for a given solar irradiation conditions, and $P_{command}$ is the actual commanded MW set point sent to the PPC.

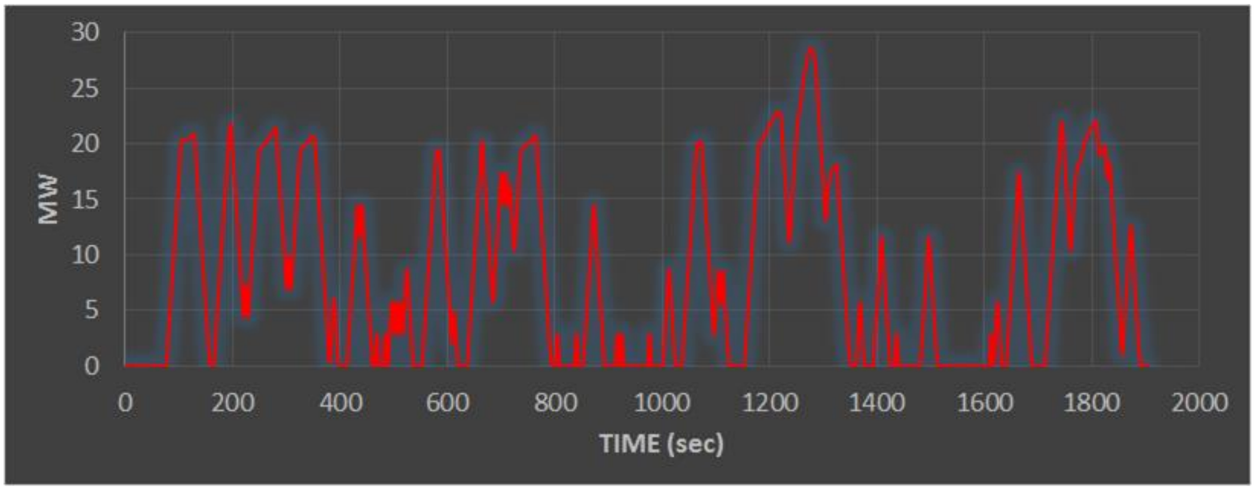


Figure 13. Historic CAISO AGC signal used in testing

This way, the response of the plant to AGC-like set point signal can be tested within a 30 MW range. The CAISO's regulation system has a significant total ramping capability for shorter periods of time. Longer ramps may cause regulation problems after faster units exhaust their regulation range. The CAISO's real-time economic dispatch software would try to return units that are not awarded service to their preferred point of operation (POP), so sufficient up and down regulation capability can be maintained. Since the plant under test was not participating in real CAISO AGC scheme, the adopted method of AGC mimicking provides sufficient approximation of real conditions since both up and down regulation characteristics of the plant can be tested this way.

For this PV plant to be able to maintain the desired regulation range (30 MW in this case), the plant PPC must be able to estimate the available aggregate peak power that all the plant's inverters can produce at any point in time. The available power is normally estimated by an algorithm that considers solar irradiation, PV module I-V characteristics and temperatures, inverter efficiencies, etc. The plant under test did not have such estimation function since it was not requested by the plant owner during construction. Instead, the project team implemented a less sophisticated approach to evaluate the available maximum power. For this purpose, a single 4 MVA inverter was taken out from active power control scheme by the First Solar team, and was set to operate at the power level determined by its maximum power point tracking (MPPT) algorithm. The measured AC power of this inverter was used as an indicator of available power for the other 79 inverters (80 inverters in total). The available maximum power was then calculated as

$$P_{available} = 79 \times P_i^{MPPT} \qquad (3)$$

Where P_i^{MPPT} is the measured AC power of the single inverter that was designated to operate at its MPPT point. Therefore, equation (2) can be re-written as

$$P_{command} = (79 \times P_i^{MPPT} - 30MW) + \Delta P_{AGC} \qquad (4)$$

So, the aggregate power command sent to the PPC for the remaining 79 inverters was calculated using equation (4). This method has inherited uncertainties since it assumes uniform solar irradiation conditions across the whole 300 MW plant. Fortunately, cloud conditions were favorable for this method to be acceptable since the sky was clear over the plant during most of the day on August 24. Of course, under moving cloud conditions the accuracy of such a method would drop significantly due to the large geographical footprint of the 300 MW PV plant. The importance of accurate peak power estimation for any type of up-regulation was also emphasized in [11], and is a crucial factor for AGC performance accuracy by PV plants.

The measured 1-sec time series for August 24, 2016 AGC tests are shown in Figure 14 - Figure 18. In particular, Figure 14 shows the results of the morning AGC test. The test started when the plant was commanded to curtail its production to a lower level (orange trace) that was 30 MW below its available peak power (green trace) in accordance to equation 4. The AGC signal was then fed to the PPC (red trace), so the plant output (yellow trace) was changing accordingly demonstrating good AGC performance by following the set point during this period of smooth power production. Similar test was conducted during peak production hour as shown in Figure 15. A zoom-in view of the same test is shown in Figure 16 allowing a closer look to the plant AGC performance. The response of the plant to each new AGC set point is almost immediate. However, there are periods when the plant is not able to reach the set point with a high level of precision. This can be explained by the internal active ramp rate limit in individual inverters that is the main source of such mismatch. The absolute control error for the same test is small as shown in Figure 16, and is confined within ±5MW range (or ±1.67% of plant rated power capacity).

Figure 14. Morning AGC test (9:47am – 10:10am)

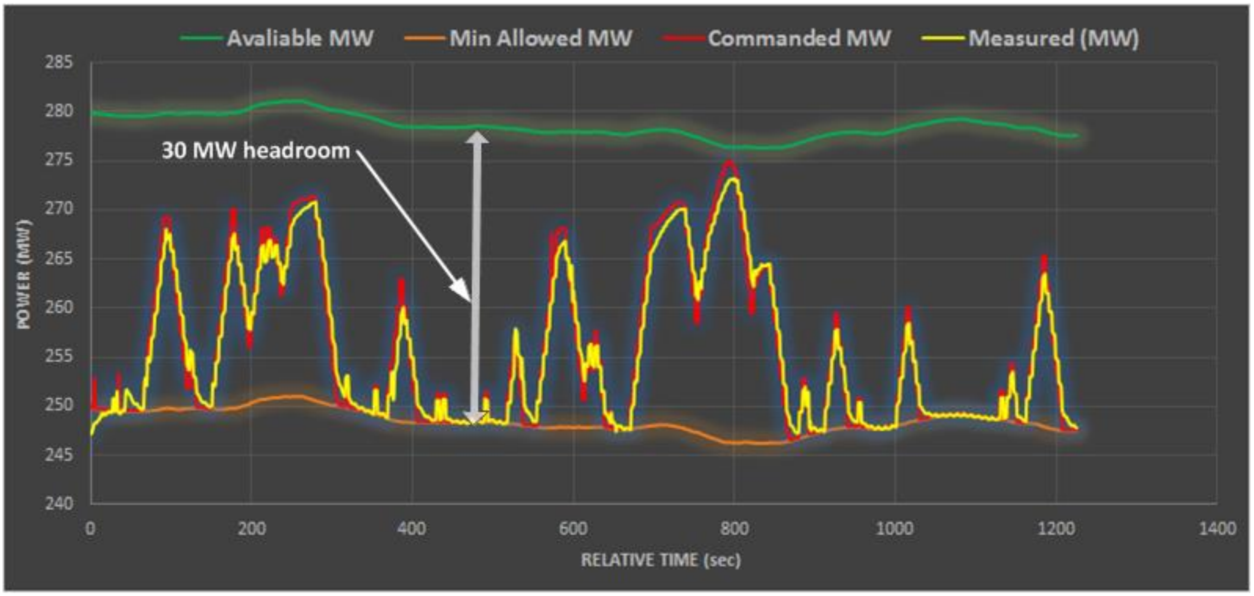


Figure 15. Mid-day AGC test (12:40pm – 1pm)

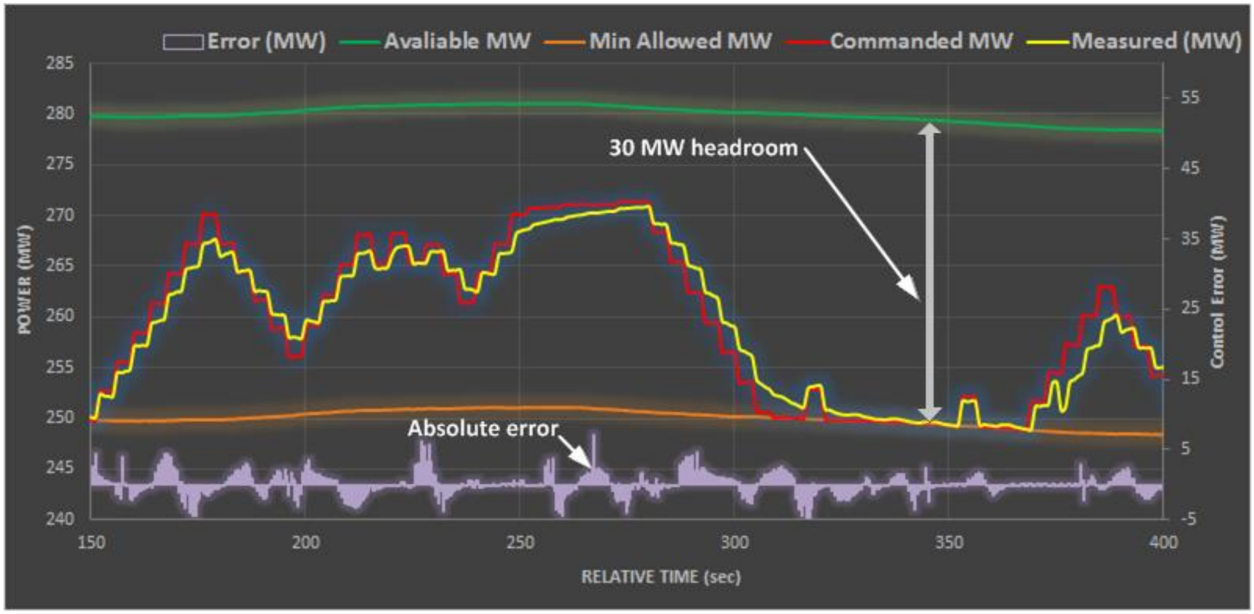


Figure 16. Mid-day AGC test zoomed-in

Result of the AGC test conducted during the afternoon are shown in Figure 17. The plant demonstrates similar AGC performance as for the previous cases. However, there was a cloud front moving over the plant in the afternoon of August 24 introducing variability in the plant output. During these periods, the available peak power from the plant was reduced significantly causing the AGC set point to decrease as well, in accordance with equation 4. However, even during these periods the plant was demonstrating good AGC performance by closely following the commanded set point as shown in Figure 18 for one such event.

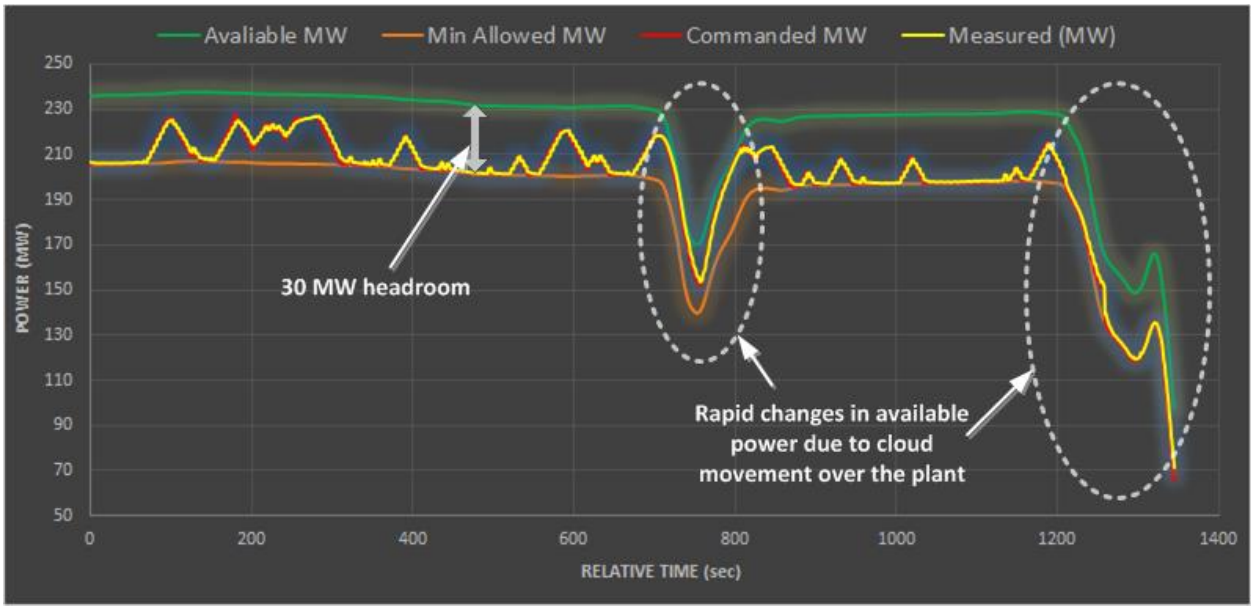


Figure 17.Afternoon AGC test (2:54pm – 3:16pm)

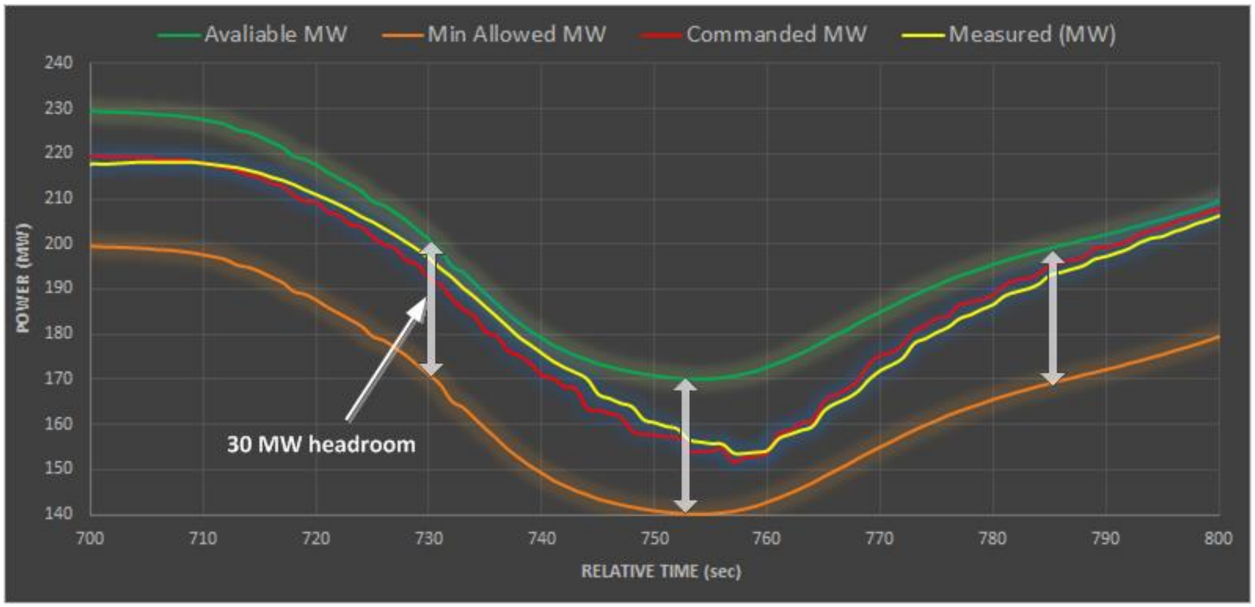


Figure 18. Afternoon AGC test zoom in

The performance results for all three AGC tests are consolidated in an X-Y plot (Figure 19) that shows linear correlation between commanded and measured plant power for the morning, noon and afternoon testing periods (red, blue and green dots respectively). Slope and offset of linear regression for each test indicate low scatter and good linearity. In addition, the R-squared values of correlation coefficients for each time period also show high degree of correlation between set point and measured plant power.

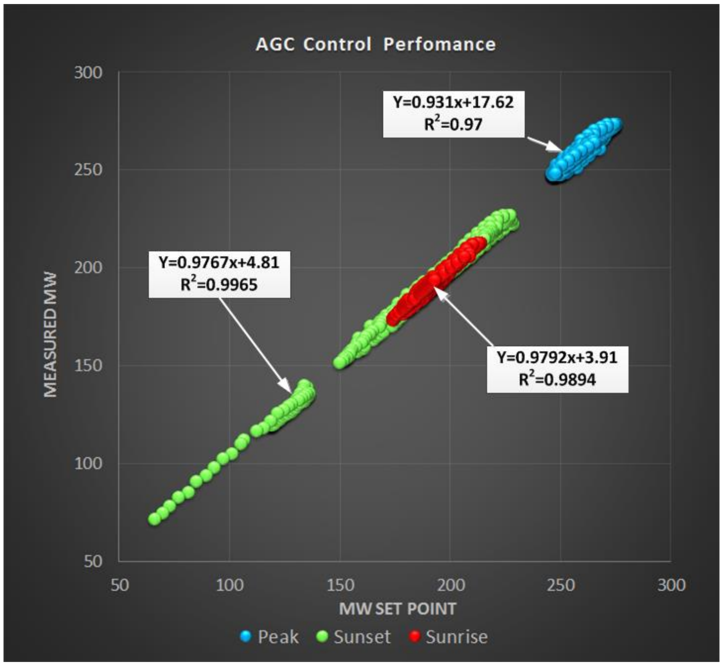


Figure 19. AGC performance for three time periods

The relative AGC control error as a percentage of installed plant capacity for all three AGC tests is shown in Figure 20 for 20 min time interval for comparison. Table 1 lists the mean, min/max and standard deviation values of the AGC control error. The mean value of AGC control error during the whole period of testing for all three data sets is very low (-0.013% of plant rated capacity) with standard deviation of error equal to 0.439%.

Figure 20: AGC control error for all three tests

Table 1. AGC control error statistics

	Sunrise	Peak	Sunset	Total for the period of testing
Mean error (% of rated power)	0.016	0.004	-0.058	-0.013
Min error (% of rated power)	-1.164	-1.854	-2.102	-2.102
Max error (% of rated power)	1.248	2.346	2.12	2.346
Standard deviation (% of rated power)	0.308	0.476	0.51	0.439

The frequency distribution of AGC control errors for all three periods of observations are shown in Figure 21 in logarithmic scale as a visual representation of the difference between the number of error magnitude occurrences for each test. These distribution shapes are not exactly symmetric but still concentrated around the center with visible tails. There are only a few occurrences of AGC control errors with large magnitudes during the periods of observation. Of course, longer testing (many days or weeks) under different cloud conditions will be required to collect sufficient statistics on AGC control accuracy. However, even such short testing opportunity allows some preliminary conclusions on accuracy of AGC control by a large utility-scale power plant. These results also suggest that relatively small and short-term energy storage can help reducing the AGC error to essentially 0% by taking care of small control inaccuracies due to cloud impact and uncertainties of peak power calculation methods.

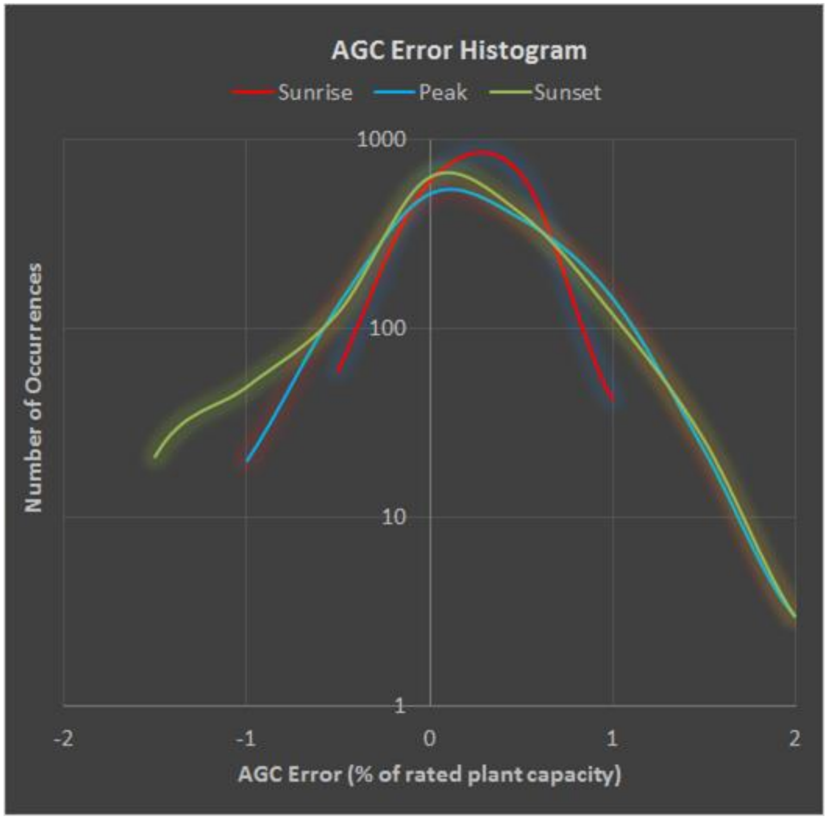


Figure 21. Distribution of AGC control error

Normally, CAISO measures the accuracy of a resource's response to EMS signals during 15-minute intervals by calculating the ratio between the sum of total 4-sec set point deviations and the sum of AGC set points. The future CAISO Resource Instructed Mileage percentage will also be calculated during 15-minute intervals. The monitored delayed response time of the plant and accuracy of the plant's response to the regulation set-point changes were used to calculate its regulation accuracy values, which are shown in Table 2 for all three testing periods. Table 3 lists the typical regulation up accuracies for CAISO's conventional generation for comparison. By comparing the PV plant testing results from Table 2 to the values for individual technologies in Table 3, a conclusion can be made that regulation accuracy by PV plant is about 24-30 points better than fast gas turbine technologies. The data from these tests will be used by the CAISO in future ancillary service market design for determining the resource-specific expected mileage for the purposes of awarding Regulation Up and Regulation Down capacity.

Table 2. Measured regulation accuracy by 300 MW PV plant

Timeframe	Solar PV Plant Test Results
Sunrise	93.7%
Middle of the Day	87.1%
Sunset	87.4%

Table 3. Typical regulation up accuracy of CAISO conventional generation

	Combined Cycle	Gas Turbine	Hydro	Limited Energy Battery Resource	Pump Storage Turbine	Steam Turbine
Regulation-Up Accuracy	**46.88%**	**63.08%**	**46.67%**	**61.35%**	**45.31%**	**40%**

4. Frequency Droop Control Tests

4.1 Rationale and description of frequency droop tests

The ability of a power system to maintain its electrical frequency within a safe range is crucial for stability and reliability. Frequency response is a measure of an interconnection's ability to stabilize the frequency immediately following the sudden loss of generation or load. An interconnected power system must have adequate resources to respond to a variety of contingency events to ensure rapid restoration of the balance between generation and load. On January 16, 2014 the Federal Energy Regulatory Commission (FERC) approved[1] Reliability Standard BAL-003-1 (Frequency Response and Frequency Bias Setting), submitted by the North American Reliability Corporation (NERC). With approving this standard, NERC created a new obligation for balancing authorities (BAs), including the CAISO, to demonstrate they have sufficient frequency response to respond to disturbances resulting in the decline of system frequency. The purpose of this initiative is to ensure the CAISO provides sufficient primary frequency response (PFR) to support system reliability while complying with the new NERC requirement [16]. NERC determines Western Interconnection's Frequency Response Obligation (IFRO) based on the largest potential generation loss of two Palo Verde generating units (2,626MW). NERC created this standard to ensure BAs have sufficient frequency response capability on hand. Like all BAs, the CAISO must plan on having an adequate amount of frequency response capability available to respond to actual frequency events. The CAISO's estimated frequency response obligation is at 258 MW/0.1 Hz. Based on historical events during 2015-2016, the CAISO recognized that its median frequency response rate may fall short of its FRO by as much as 100 MW/0.1Hz [16]. From this perspective, participation of curtailed PV power plants in CAISO frequency response could help in addressing this potential deficiency. The objective of the frequency response test conducted under this project was to demonstrate that the plant can provide a response in accordance with 5% and 3% droop settings through its governor-like control system.

The definition of implemented droop control for PV is the same as that for conventional generators:

$$Droop = \frac{\Delta P / P_{rated}}{\Delta f / 60Hz} \tag{5}$$

Plant rated active power (300 MW) is used in equation (5) for the droop setting calculations. For the purposes of the droop test, the plant was set to operate at a curtailed power level that was 10% lower than the available estimated peak power. The PPC was programmed to change the power output of the plant in accordance with a symmetric droop characteristic, shown in Figure 22 at both 5% and 3% droop value. The upper limit of the droop curve was the available plant power, and the lower limit was at a level that was 20% below the then-available peak power. The implemented droop curve also had a ±36 mHz frequency dead band.

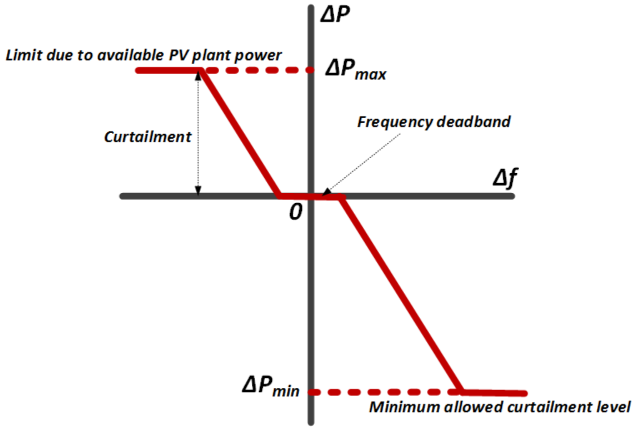


Figure 22. Frequency droop characteristic

The frequency droop capability of the plant was tested using the actual over and under-frequency events in Western Interconnection measured by NREL in Colorado (Figure 23 and Figure 24 respectively).

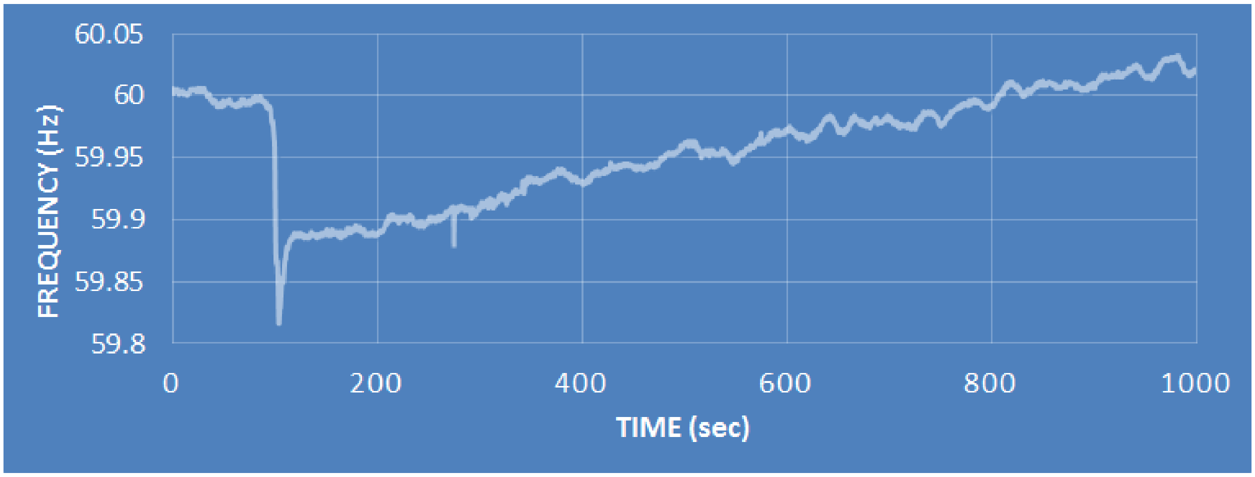


Figure 23. Under-frequency event

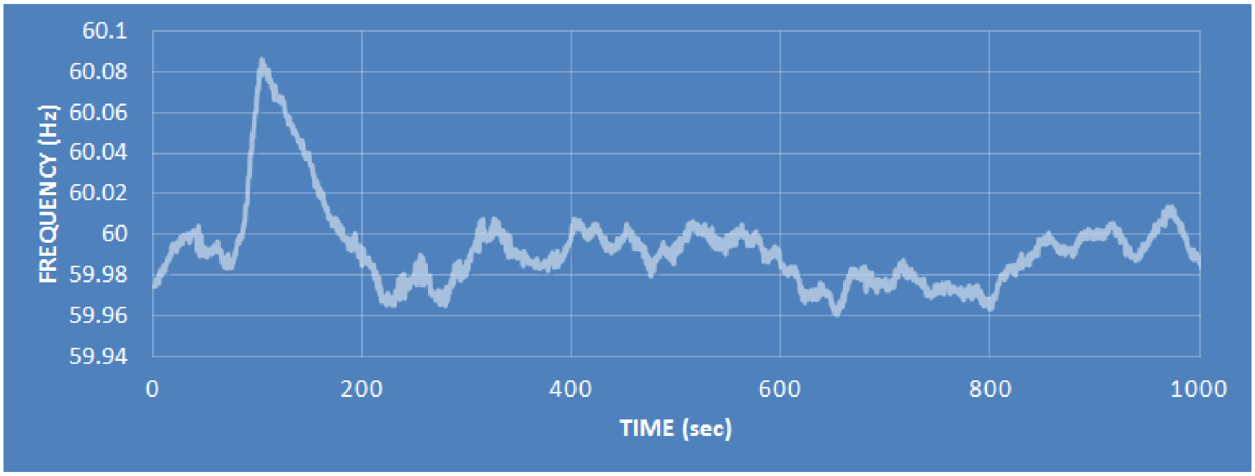


Figure 24. Over-frequency event

The frequency event time series shown in Figure 23 and Figure 24 were provided to the PPC, so the plant can demonstrate a frequency response as if it is exposed to a real frequency event measured at the plant POI. This is the common method for testing the frequency response of inverter-coupled generation since waiting for a real frequency event to occur in the power system may be time consuming since large contingency events do not happen very often (2-3 times per month for the Western Interconnection). The active power ramp-rate limit in PPC was set at 600 MW/min (10 MW/sec) during droop control tests.

4.2 Droop test results

The 5% and 3% frequency droop tests on the 300 MW PV power plant were conducted during August 24, 2016. For this purpose, the First Solar team remotely set the PPC into droop control mode in accordance with the control method shown in Figure 22 with 5% and 3% droop value and 10% power curtailment. The minimum allowed power level for down regulation was set to 20% below available peak power for all droop tests (to minimize plant revenue losses).

4.2.1 Droop tests during under-frequency event

The results of one 3% droop test during the morning on August 24, 2016, are shown in Figure 25. The plant active power response in MW to the under-frequency event was measured by the PMU at the plant POI. The calculated active power time series show that the plant increases its power output during the initial grid frequency decline, and then gradually returns to its original pre-test level as frequency returned to its normal pre-fault level. The droop response of the plant can be observed on the X-Y plot shown in Figure 26 where a linear dependence between frequency and measured power can be observed once the frequency deviation exceeds the dead band.

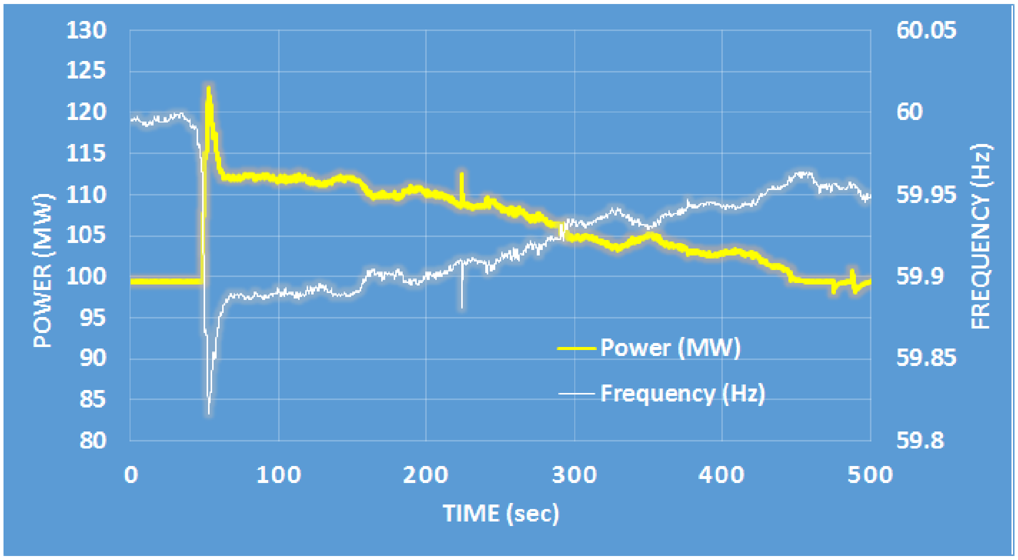


Figure 25. Example of plant response to under-frequency event (3% droop test during sunrise)

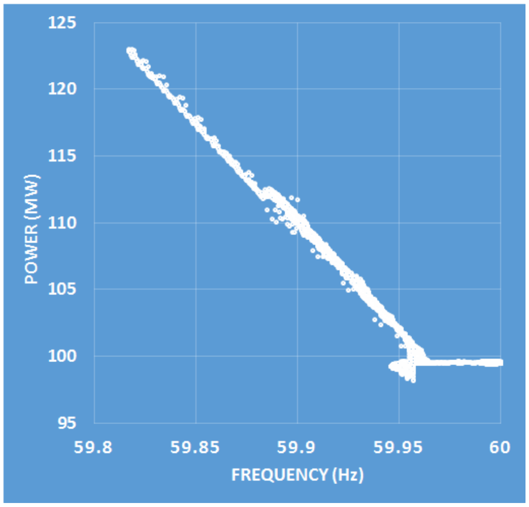


Figure 26. Measured droop characteristic for under-frequency event (3% droop test during sunrise)

Similarly, 3% and 5% droop tests were conducted during mid-day (peak solar production period) and during the afternoon. Example test results for these periods are shown in Figure 27 (a,b) and Figure 29. Some non-linearity in the plant response was observed during these tests when frequency deviation was exceeding 120 mHz from its pre-fault level causing some mismatch between expected and actual droop response. Such non-linearity was not observed during the morning droop tests when the solar resource was increasing steadily during the test under clear sky conditions. One reason for such mismatch can be decreasing solar resource during the afternoon tests and increased resource variability due to cloud conditions in the afternoon. Obviously, such non-linearity can be mitigated by further fine-tuning of the PPC control parameters, and the First Solar team will address this issue in the future.

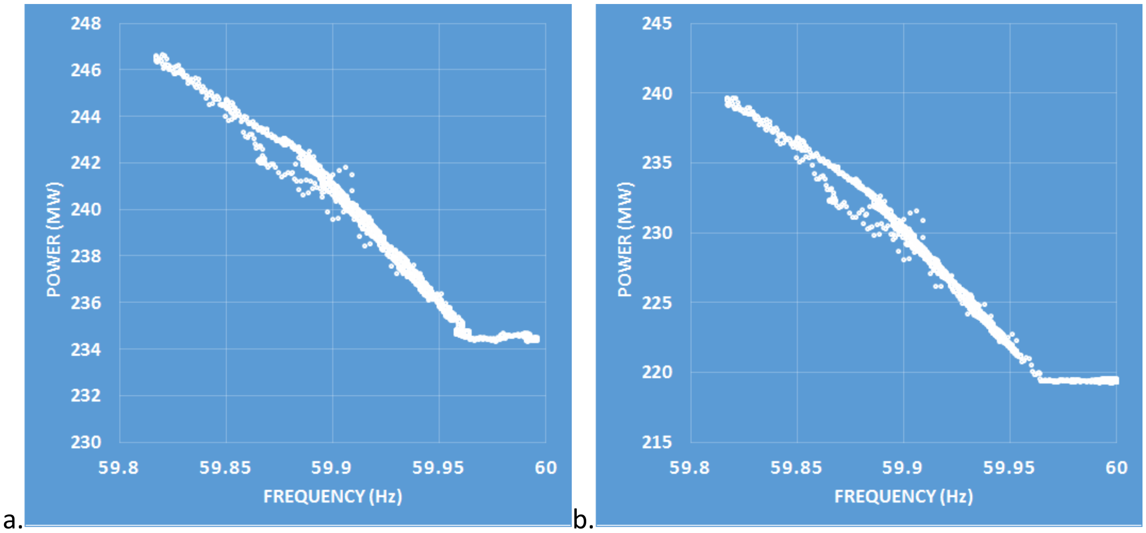


Figure 27. Measured droop characteristics for under-frequency event (a - 5% droop test, b – 3% droop test during mid-day)

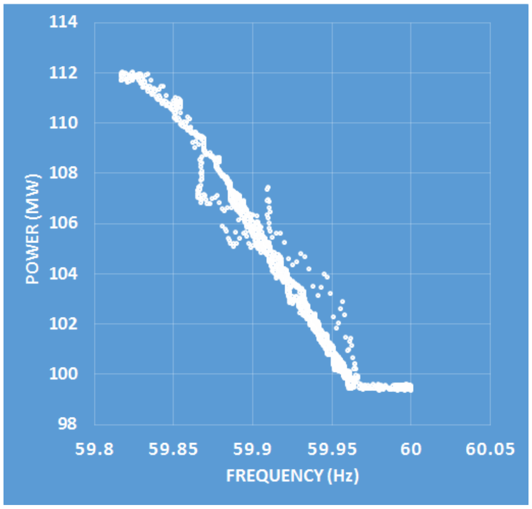


Figure 28. Measured droop characteristics for under-frequency event (5% droop test during sunset)

Results of individual droop tests are shown in greater details in Figure 29 - Figure 33. The first plot in each figure shows the data points scattered around the calculated target droop characteristic (Figure 29a-Figure 33a). In these X-Y plots, the X-axis represents the frequency deviation Δf (or change in frequency) from its pre-fault value, calculated as:

$$\Delta f = f_{grid} - 60Hz \qquad (6)$$

Where f_{grid} is the value of grid frequency from the event time series.

The Y-axis represents the plant active power response $\Delta P_{measured}$ (or change in plant active power output) calculated as:

$$\Delta P_{measured} = P_{actual} - P_{max.estimated} \qquad (7)$$

Where P_{actual} is the measured plant active power at POI, and $P_{max.estimated}$ – is the estimated peak power for a given level of solar resource.

The calculated plant response $\Delta P_{calculated}$ (or target response) for a given droop value can be calculated as

$$\Delta P_{calculated} = \frac{\Delta f}{60Hz} \cdot \frac{1}{Droop} \cdot P_{nom} \qquad (8)$$

Where $P_{nom} = 300\ MW$ is the plant's nameplate capacity.

The droop control error is then calculated as a difference between calculated target and actual plant response for any given droop setting:

$$Error = \Delta P_{calculated} - \Delta P_{measured} \qquad (9)$$

The frequency distribution of control error data for each droop test along with error statistics data are shown in Figure 29b-Figure 33b. The detailed comparison of these tests results concluded that the PV plant has demonstrated a satisfactory droop performance during under-frequency events for morning, noon and afternoon time frames. Some non-linearities in the response can be further improved by fine-tuning of controller parameters. The observed scatter around the target response is due to short term solar resource variability and can be mitigated if such response is generated by a number of PV plants within a larger geographical footprint.

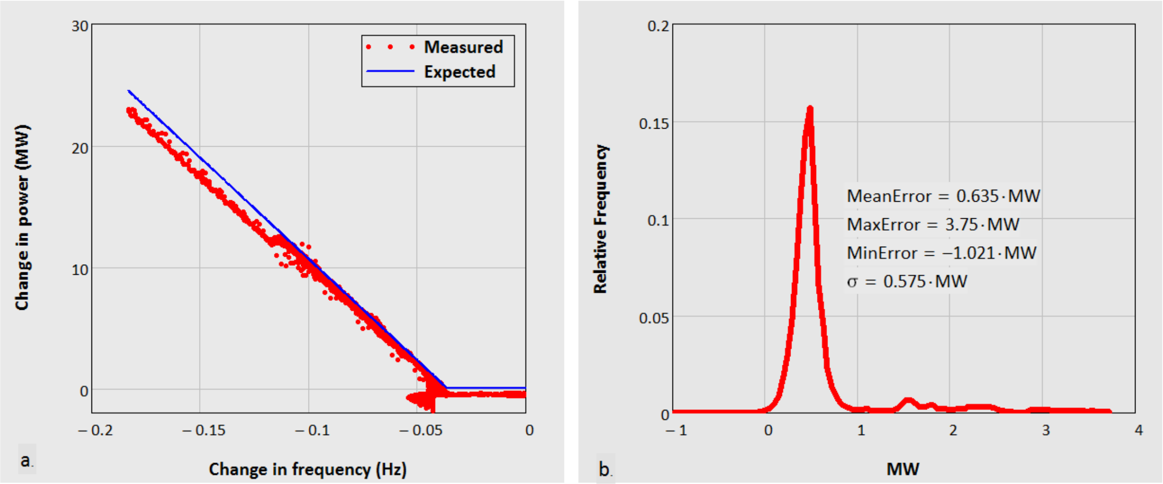


Figure 29. Results (a) and control error (b) during sunrise 3% droop test for under-frequency event

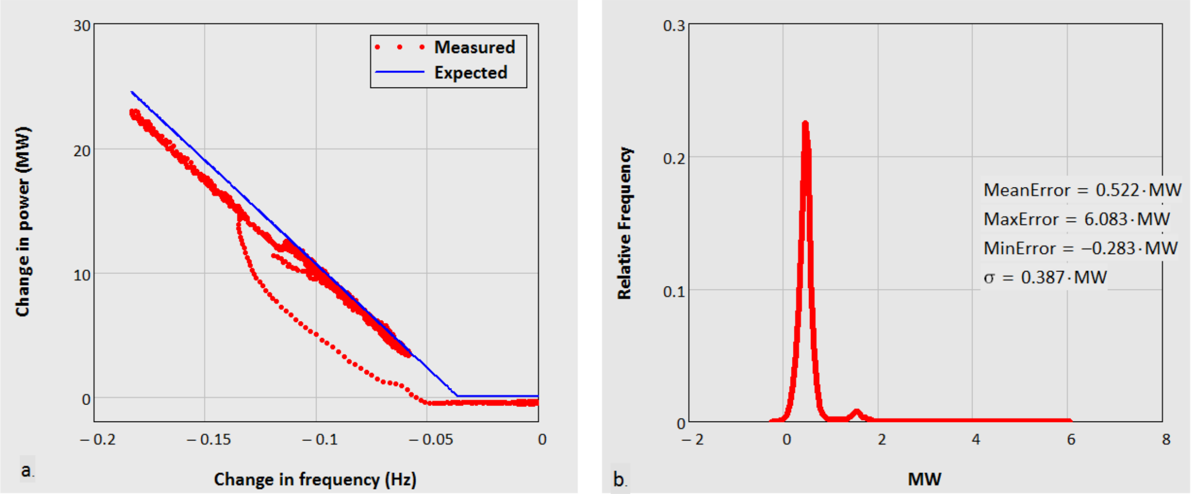


Figure 30. Results (a) and control error (b) during second sunrise 3% droop test for under-frequency event

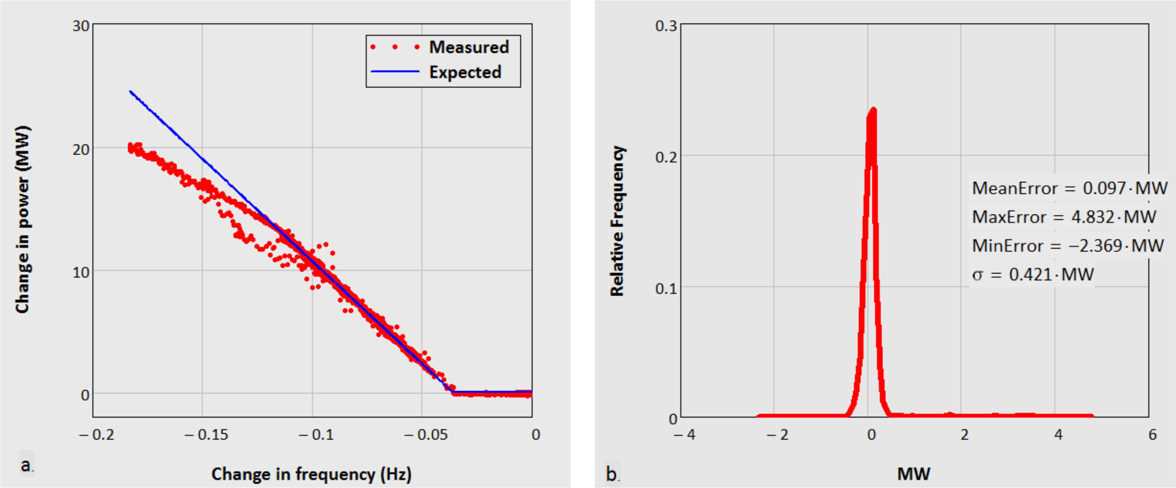


Figure 31. Results (a) and control error (b) during mid-day 3% droop test for under-frequency event

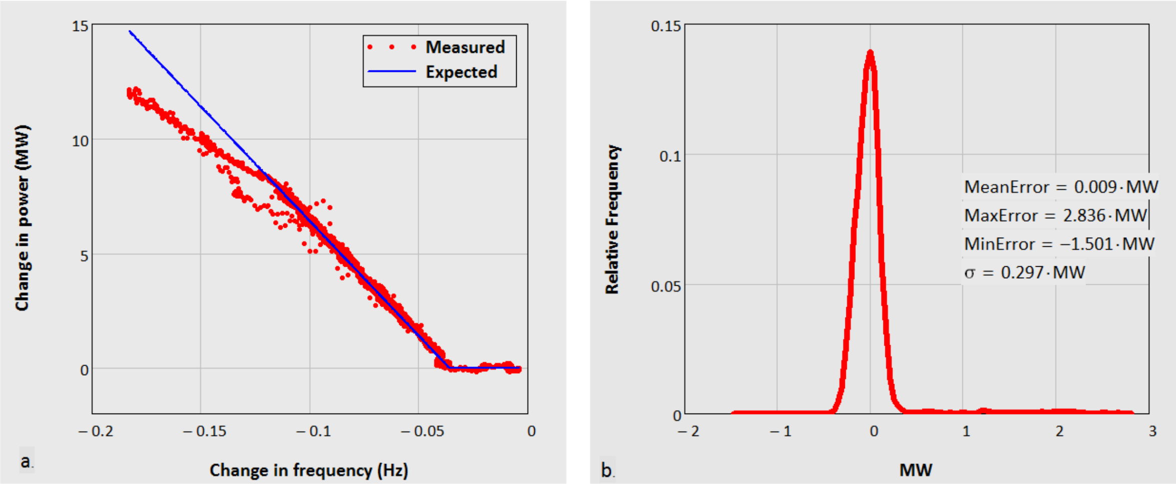


Figure 32. Results (a) and control error (b) during mid-day 5% droop test for under-frequency event

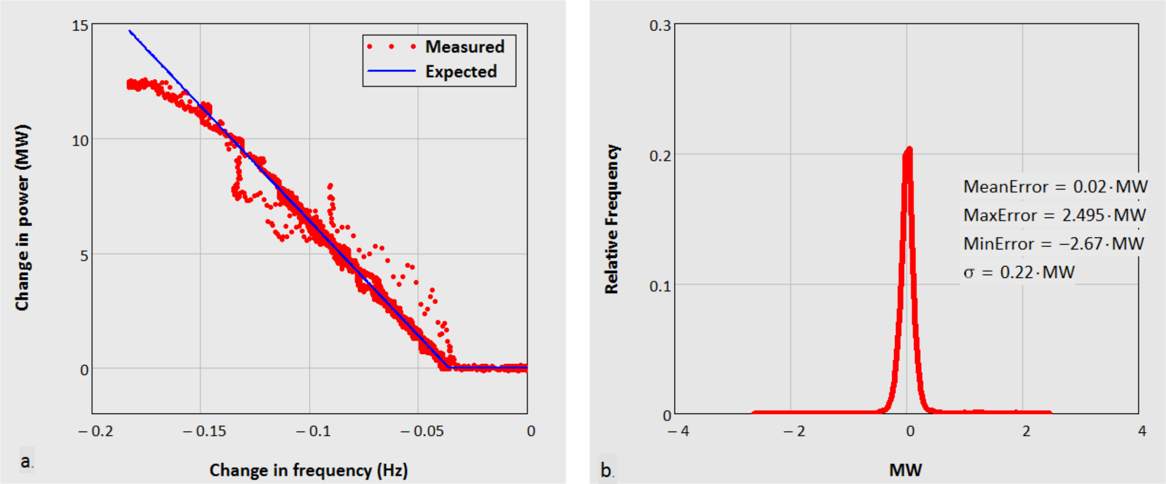


Figure 33. Results (a) and control error (b) during sunset 5% droop test for under-frequency event

Table 4 and Table 5 show the control error statistics for under-frequency droop tests in absolute MW units and percentage of plant capacity respectively. Despite of observed non-linearities and scatter, the mean control error is very small ranging between 0% and 0.21% of the plant's rated capacity. The standard deviation control error is also small (0.07 – 0.19% of rated capacity). The largest measured positive and negative error values are 2.03% and -0.89% of the plant's rated capacity. Figure 34 shows the consolidated data for many up-regulation tests for comparison purposes.

Table 4. Droop control error statistics (absolute values in MWs)

Test type	Mean Error, [MW]	Max +Error [MW]	Max –Error [MW]	STD [MW]
3% droop, sunrise	0.635	3.75	-1.02	0.575
3% droop, sunrise	0.522	6.08	-0.28	0.387
3% droop, mid-day	0.097	4.83	-2.37	0.42
5% droop, mid-day	0.009	2.84	-1.5	0.297
5% droop, sunset	0.02	2.5	-2.67	0.22

Table 5. Droop control error statistics (percentage of plant rated capacity)

Test type	Mean Error, [%]	Max +Error [%]	Max –Error [%]	STD [%]
3% droop, sunrise	0.21	1.25	-0.34	0.19
3% droop, sunrise	0.17	2.03	-0.09	0.13
3% droop, mid-day	0.03	1.61	-0.79	0.14
5% droop, mid-day	0.00	0.95	-0.5	0.1
5% droop, sunset	0.01	0.83	-0.89	0.07

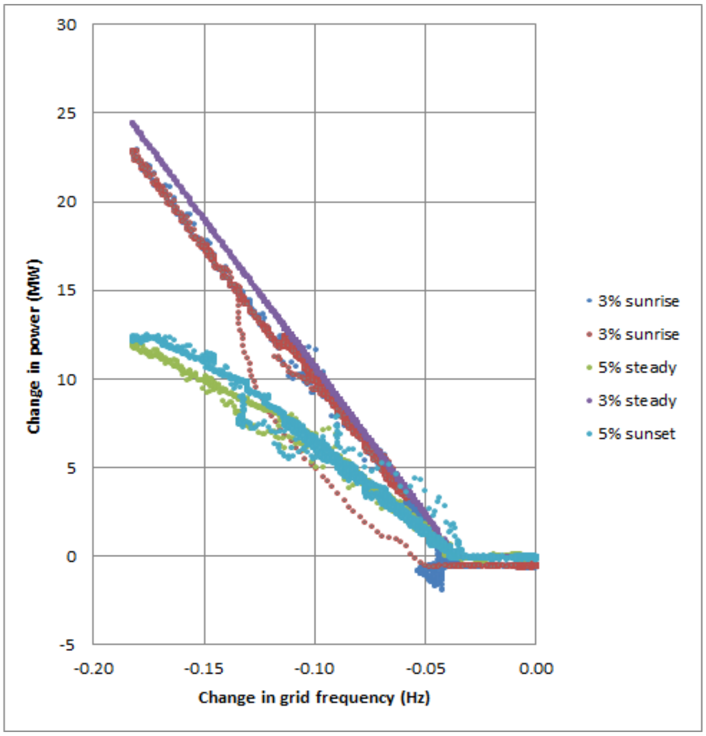


Figure 34. Consolidated under-frequency droop test results

4.2.2 Frequency droop tests during over-frequency event

Frequency droop tests for over-frequency events were also conducted on August 24, 2016. The results of one 5% droop test during the morning on August 24 are shown Figure 35. The plant response to the over-frequency event was measured by PMU at the plant POI. The calculated active power time series shows that the plant decreases its power output during the initial grid frequency increase, and then gradually returns to its original pre-test level as frequency returned to its normal pre-fault level. The droop response of the plant from several tests can be observed on X-Y plots shown in Figure 36(a, b) and Figure 37 where a linear dependence between frequency and measured power can be observed once the frequency deviation exceeds the dead band. The plant demonstrated consistent and accurate down-regulation performance during all over-frequency droop tests.

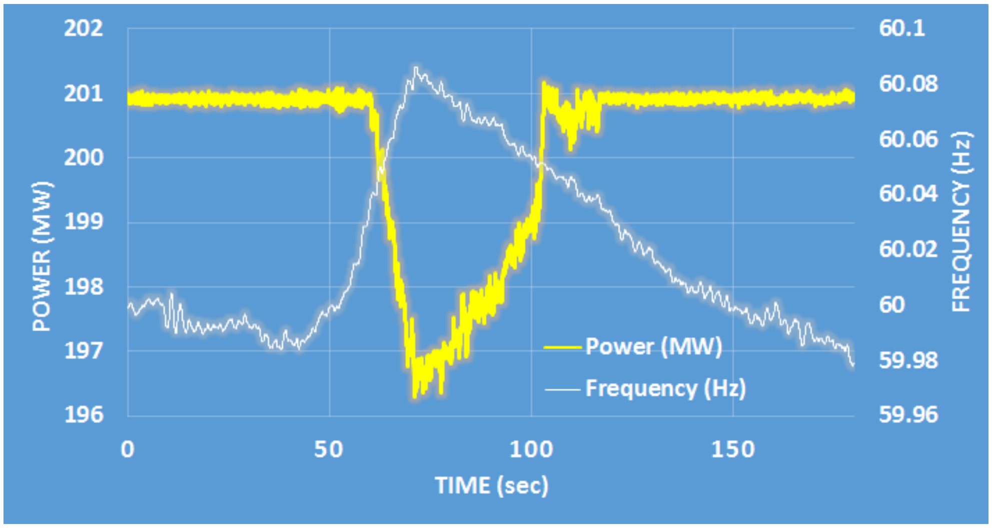


Figure 35. Example of plant response to over-frequency event (5% droop test during sunrise)

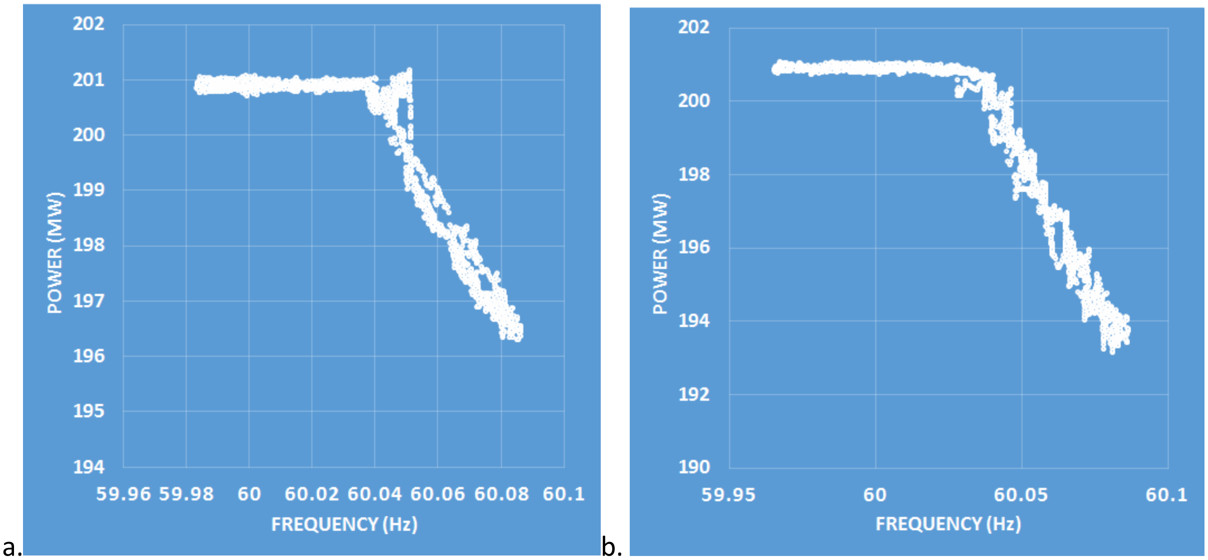


Figure 36. Measured droop characteristics for over-frequency event (a - 5% droop test, b – 3% droop test during midday)

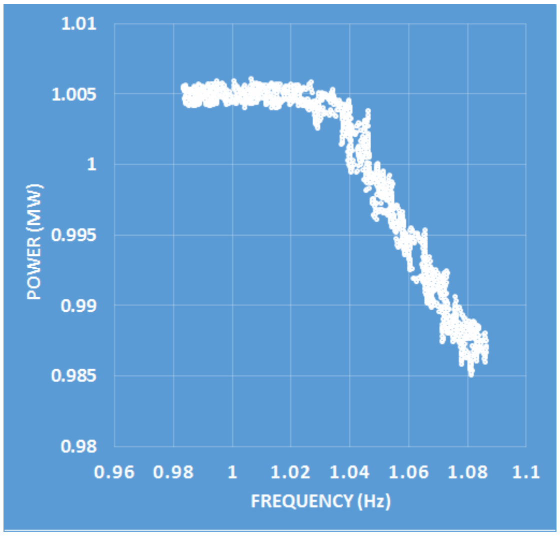


Figure 37. Measured droop characteristics for over-frequency event (5% droop test during sunset)

A PV plant must operate in curtailed mode to provide enough reserve for PFR response 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 plant. The reserve available (i.e., headroom) is the available power curtailed, which is shown as the reserve between the operational point and P_0 in Figure 38. A non-symmetric droop curve is possible with solar PV power depending on system needs as shown in Figure 38. More aggressive droops (e.g. 1% or 2%) can be implemented for over-frequency regulation since PV plants are able of providing very fast curtailment. If required by reliability consideration, PV plants can be programmed to provide non-symmetric droop response similar to the one depicted in the conceptual graph in Figure 38. Such non-symmetric droop response is planned to be demonstrated in future stages of this testing project.

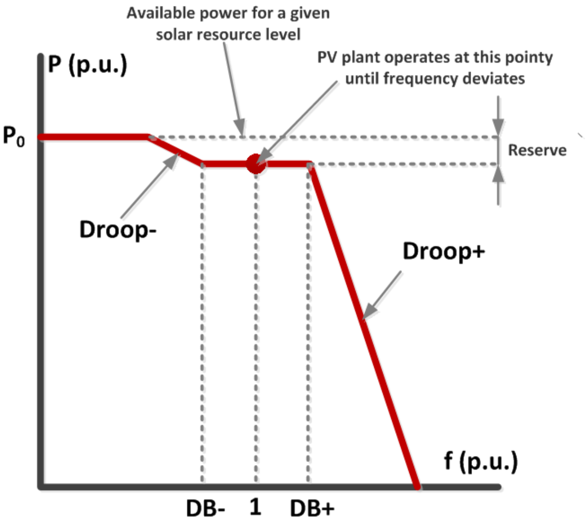


Figure 38. Concept of non-symmetric droop characteristic for PV plants

5. Reactive Power and Voltage Control Tests

5.1 Rationale and description of reactive power tests

Voltage on the North American bulk system is normally regulated by generator operators, which typically are provided with voltage schedules by Transmission Operators [17]. The growing level of penetration of variable wind and solar generation has led to the need for them to contribute to power systems voltage and reactive regulation since in the past the bulk system voltage regulation was provided almost exclusively by synchronous generators. According to FERC Large Generator Interconnection Agreement (LGIA) [18], the generally accepted power factor requirement of large generator is ±0.95. In conventional power plants with synchronous generators, the reactive power range is normally defined as dynamic. So, the synchronous generators need to continuously adjust their reactive power production or absorption within a power factor range of ±0.95. For PV power plants, the reactive power requirements are not well defined. FERC Order 661-A [19] is applicable to wind generators but sometimes applied to PV plants as well. It also requires to have a power factor range of ±0.95 measured at the POI, and provide sufficient dynamic voltage support if required to ensure safety and reliability (the requirement for dynamic voltage support is normally determined during interconnection studies). Utility-scale wind plants are designed to meet the ±0.95 power factor requirements. However, the common practice in the PV industry is to configure PV inverters to operate at unity power factor. It is expected that similar interconnection requirements for power factor range and low-voltage ride-through will be formulated for PV in the near future. In order to meet this requirement, the PV inverters need to have MVA ratings large enough to handle full active and reactive current.

In its recent Order 827, FERC issued a final rule requiring all newly interconnecting non-synchronous generators, including wind generators, to design their facilities to be capable of providing reactive power [20]. The generating facilities have to be capable of maintaining a composite power delivery at continuous rated power output at the high-side of the generation substation at ±0.95 power factors.

Conventional synchronous generators of power plants have reactive power capability that is typically described as “D curve”, as shown in Figure 39. The reactive power capability of conventional power plants is limited by many factors including their maximum and minimum load capability, thermal limitations due to 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 PV inverter is determined by its current limit only. With proper MW and MVA rating, the PV inverter should be able to operate at full current with reactive power capability similar to the one shown in Figure 39. In general, for the same MVA rating, a PV power plant is expected to have much superior reactive power capability than a conventional synchronous generator-based plant as indicated notionally in Figure 39. In principle, PV inverters can provide reactive power support at zero power, similar to a STATCOM. However, this functionality is not standard since PV inverters are disconnected from the grid at night.

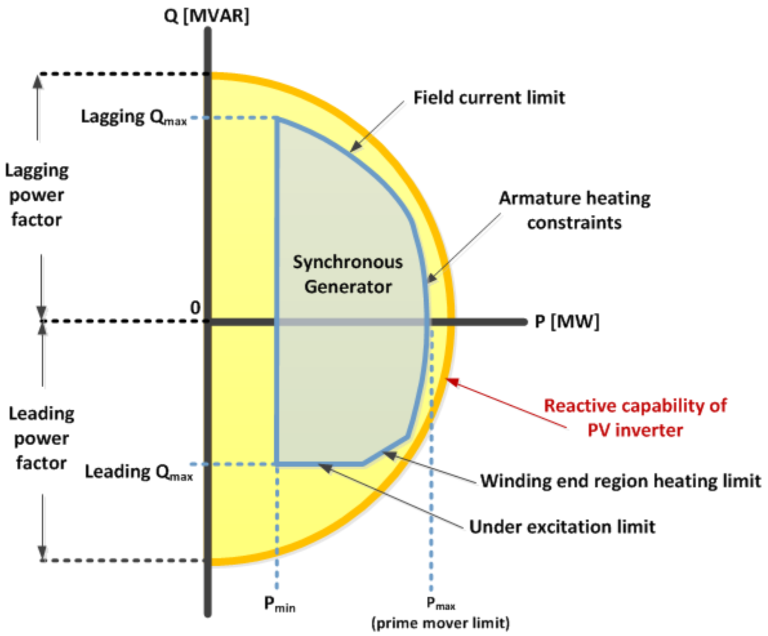


Figure 39. Comparison of reactive power capability for synchronous generator and PV inverter of same MVA and MW ratings

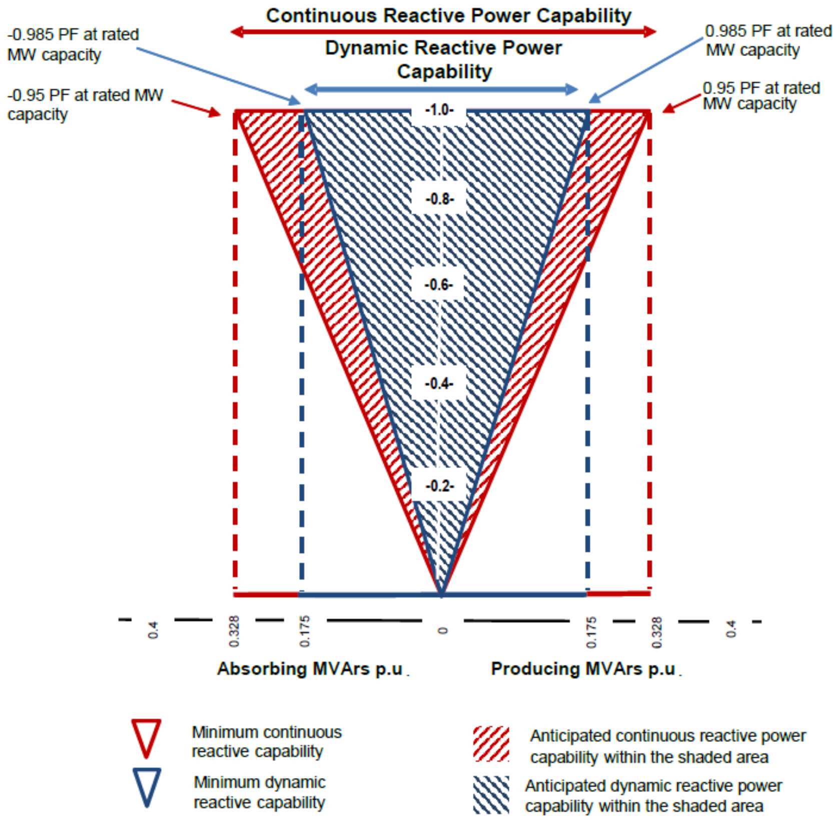


Figure 40. Proposed reactive power capability for asynchronous resources (source: CAISO)

In is proposed Reactive Power capability characteristic for asynchronous generation (Figure 40) the CAISO defined the requirements for dynamic and continuous reactive power performance by such resources [21]. The red vertical lines shown in Figure 40 represent the expected reactive capability of the asynchronous generating plant at the high side of the generator step-up bank. At all levels of real power output, the plant is expected to produce or absorb reactive power equivalent to approximately 33% of the plant's actual real-power output. For example, at maximum 300 MW real power capability of the plant, the expected dynamic reactive capability should be 100 MVARS lagging or 100 MVARS leading. Also, at 50% real power output, the expected reactive capability should be 50 MVARS lagging or 50 MVARS leading, and at zero MW output, the expected reactive output should be zero. Figure 41 shows the expected reactive capability of the 300 MW PV plant under test if it has to comply with the proposed CAISO's requirement for Asynchronous Generating Facility at the POI. The PV plant is supposed to absorb or produce 100 MVAR of reactive power when operating at full MW capacity at power factor of -0.95 or +0.95 respectively.

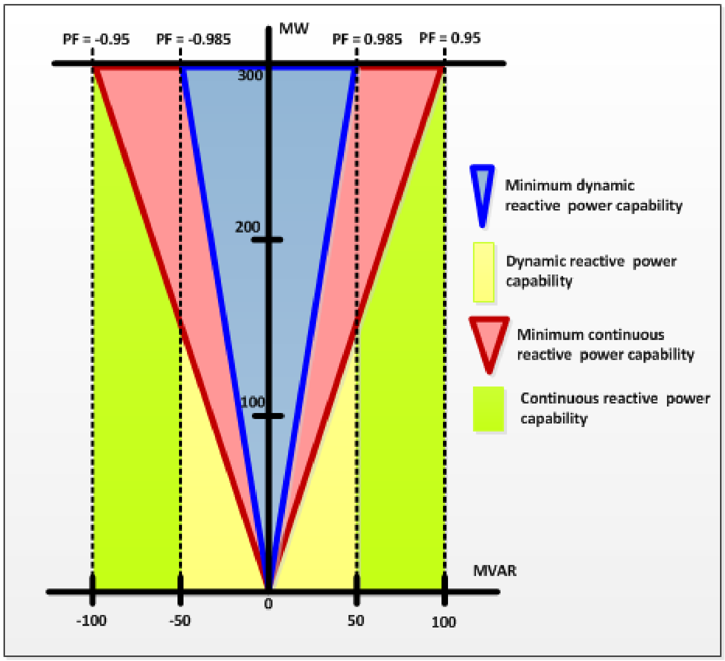


Figure 41. CAISO proposed reactive capability applied to the 300 MW PV plant under testing

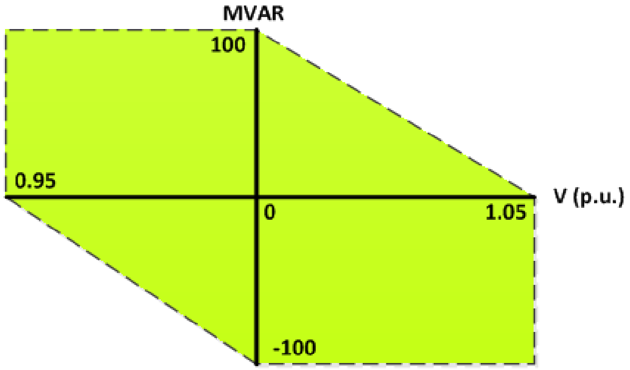


Figure 42. Plant reactive power capability at different voltage levels at full MW output

The voltage at the POI may 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. at the POI. 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. The proposed capability at different voltage levels applied to the 300 MW PV plant at full MW production level is shown in Figure 42.

The CAISO proposed to adopt a uniform requirement of asynchronous inverter-coupled resources to provide reactive power capability and voltage regulation as shown in Figure 40 [21]. According to CAISO draft proposal on Reactive Power and Financial Compensation, the asynchronous generating facility shall have dynamic and continuous reactive capability for power factor ranges of ±0.985 and ±0.95 respectively. Through its initiative the CAISO has explored mechanisms to compensate resources for the capability and provision of reactive power. While some other regions make capability payments, there are regions where transmission providers make no payments for reactive power capability. These regions conclude that requiring capability for such operation is a requirement under good utility practice and a necessary condition for conducting normal business [21].

The primary objective of the reactive power test was to demonstrate the capability of the PV plant to operate in the voltage-regulation mode within 0.95 lead/lag 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.

The tests were conducted at three different real power output levels. (1) at maximum production during the middle of the day, (2) during sunset when the plant is about 50% of its maximum capability, and (3) during sunset when the plant is close to zero production. Measurements were conducted to verify the plant's capability to absorb and produce reactive power in accordance to Figure 40, within ±100 MVAR range during various levels of real power output.

- The plant was first tested at its maximum real power output for a given irradiance level. At maximum real power output, the plant must demonstrate that it can produce approximately 33% of real output as dynamic reactive. Similarly, at maximum real power output, the plant must demonstrate it can absorb approximately 33% of its real power output as reactive output.

- During sunset, as the solar production drops off to about 50% of the resource maximum capability, the plant must demonstrate it can produce and absorb approximately 33% of its real power output as dynamic reactive output.
- During sunset, as the plant production approaches zero MW, the plant must demonstrate it can produce and absorb approximately 33% of its real power output as dynamic reactive output.

5.2 Results of reactive capability power tests

The plant reactive power capability was tested at two different power levels during Aug 23 and 24, 2016. First, the plant's reactive power capability was measured during the number of tests when plant was producing high levels of active powers (250 MW and higher). Then, the reactive power capability was measured at extremely low levels of MW production (less than 5MW). The results of both tests are consolidated in MVAR vs. MW graph in Figure 43 where the blue dots represent the data points measured by the plant's PMU. The measurements are compared to the proposed CAISO reactive power requirement for asynchronous generation (yellow triangle), demonstrating that the plant meets the expected reactive power capability. In addition, the plant is capable of producing and absorbing reactive power at close to zero power production. Another, more articulate view of the same test results, is shown in 3D in Figure 44 which combines measured MW, MVAR and POI voltage allowing positioning of measured data points with respect to proposed CAISO requirements.

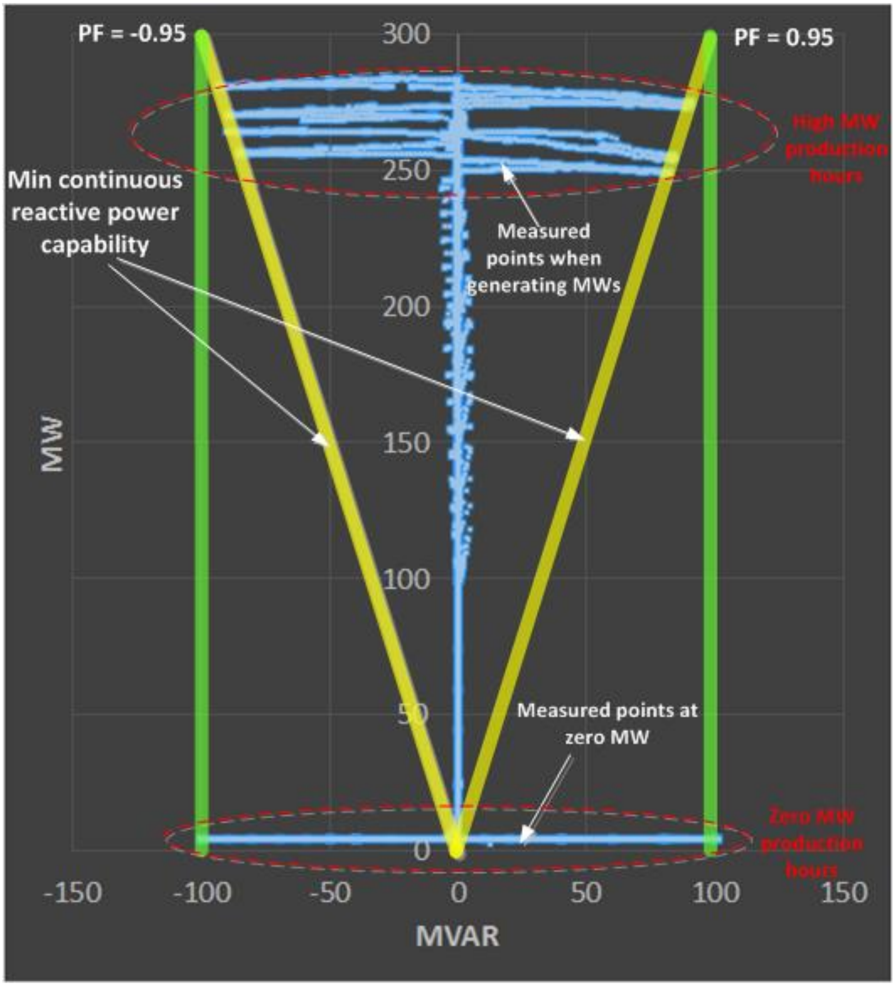


Figure 43. Measured reactive power capability at POI

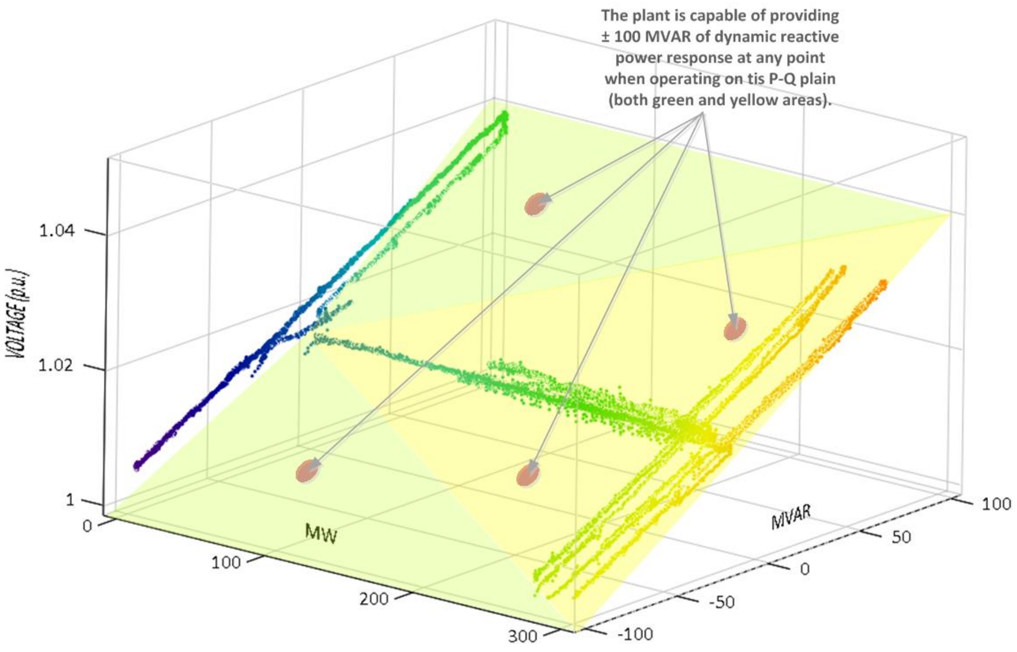


Figure 44. Measured reactive power capability and voltages at POI

The voltage limit control test was conducted to verify the ability of the plant control system capability of maintaining a power factor target at the same time maintaining voltage at the POI between the low and high limits (0.95 p.u. and 1.05 p.u. respectively) as shown in Figure 45. First, the plant was operating at nearly maximum active power generation in close to unity power factor control mode. An artificial POI voltage signal was provided to the plant controller to override the real measurement. While in PF control mode, the control automatically switched to voltage limit mode to maintain voltage within safe operating limits. Upon completion of POI voltage increase or decrease with the PF near the unity value, the control system switches back to PF control mode.

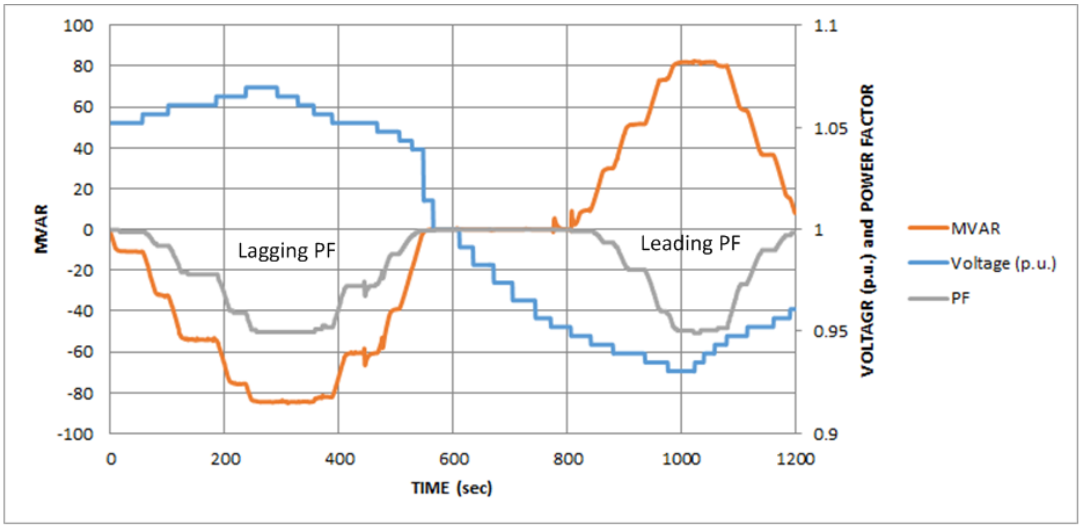


Figure 45. Results of voltage limit control test

The same test is also shown in Figure 46, where the measured reactive power is compared to the reactive power capability window from Figure 42. As can be seen in Figure 46, the plant is fully capable of operating within CAISO proposed window at PF=±0.95.

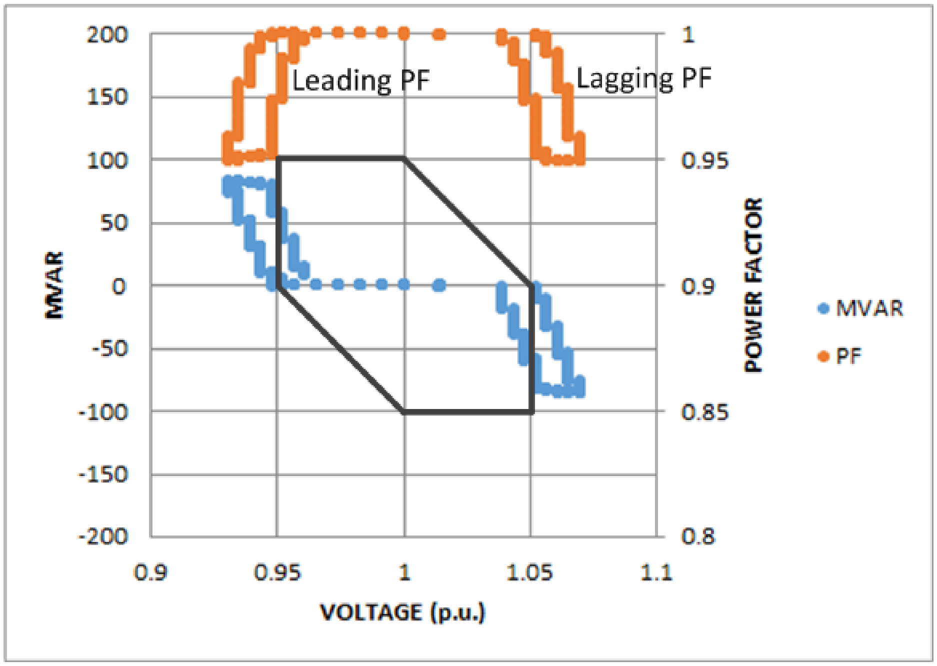


Figure 46. Voltage limit control test and reactive pwoer capability

In addition, the plant was tested to demonstrate the control operation in power factor control mode and characterize control system response to changes in PF set point. Reactive power ramp rates and PF limits for this test were specified at ±100 MVAR/min and ±0.95 respectively. The results of leading and lagging power factor control tests are shown in Figure 47. For both tests the system was operating at nearly full power output. It reaches its PF targets with specified ramp rates without any oscillation and stability issues.

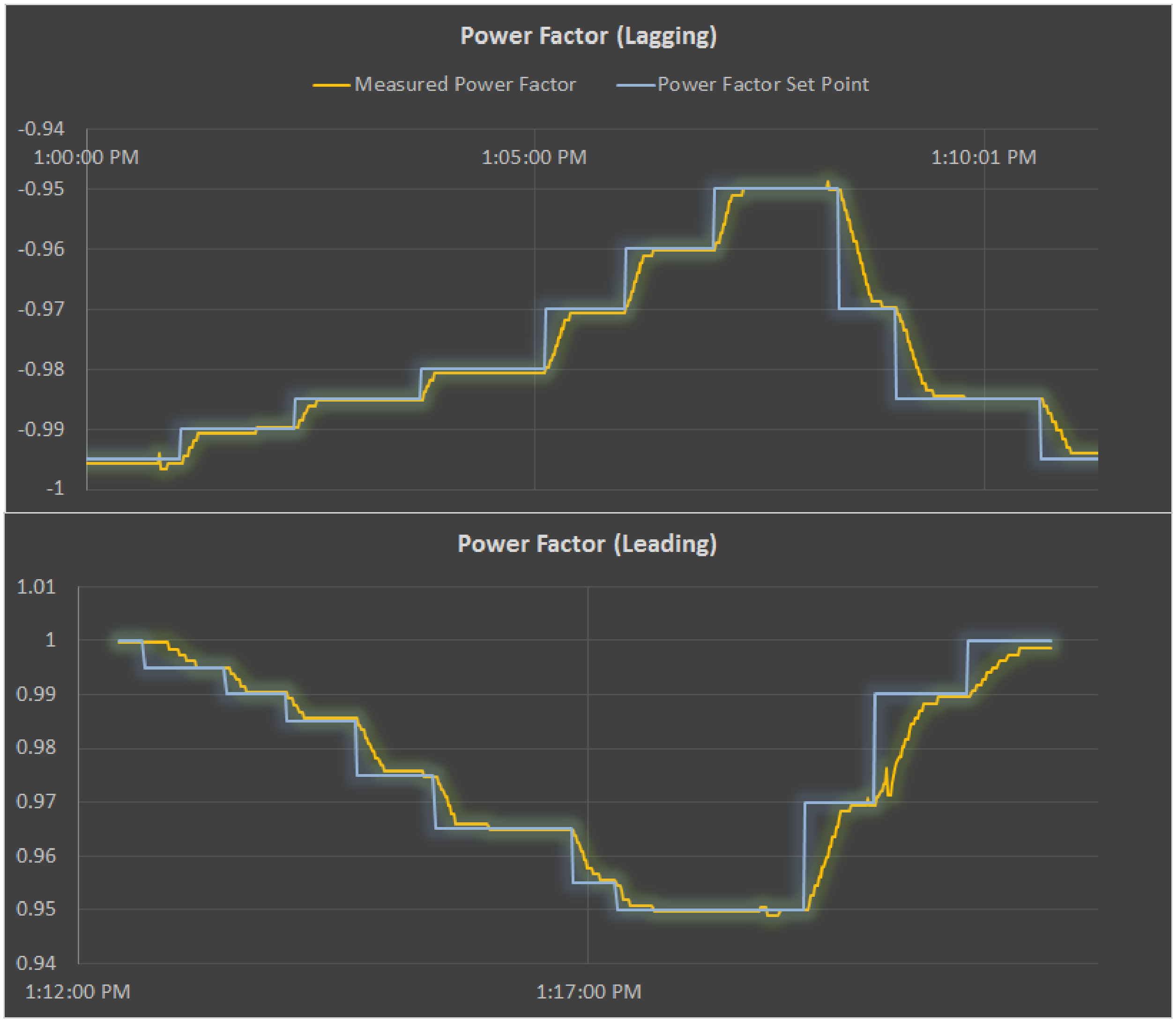


Figure 47. Lagging and leading power factor control tests

Results of reactive power set point control test are shown in Figure 48. This test was conducted during high power generation period, and was intended to demonstrate the ability of the plant to maintain capacitive or inductive VARs at the POI. As seen from Figure 48, the plant was fully capable of following the reactive power set points with prescribed reactive power ramp rates.

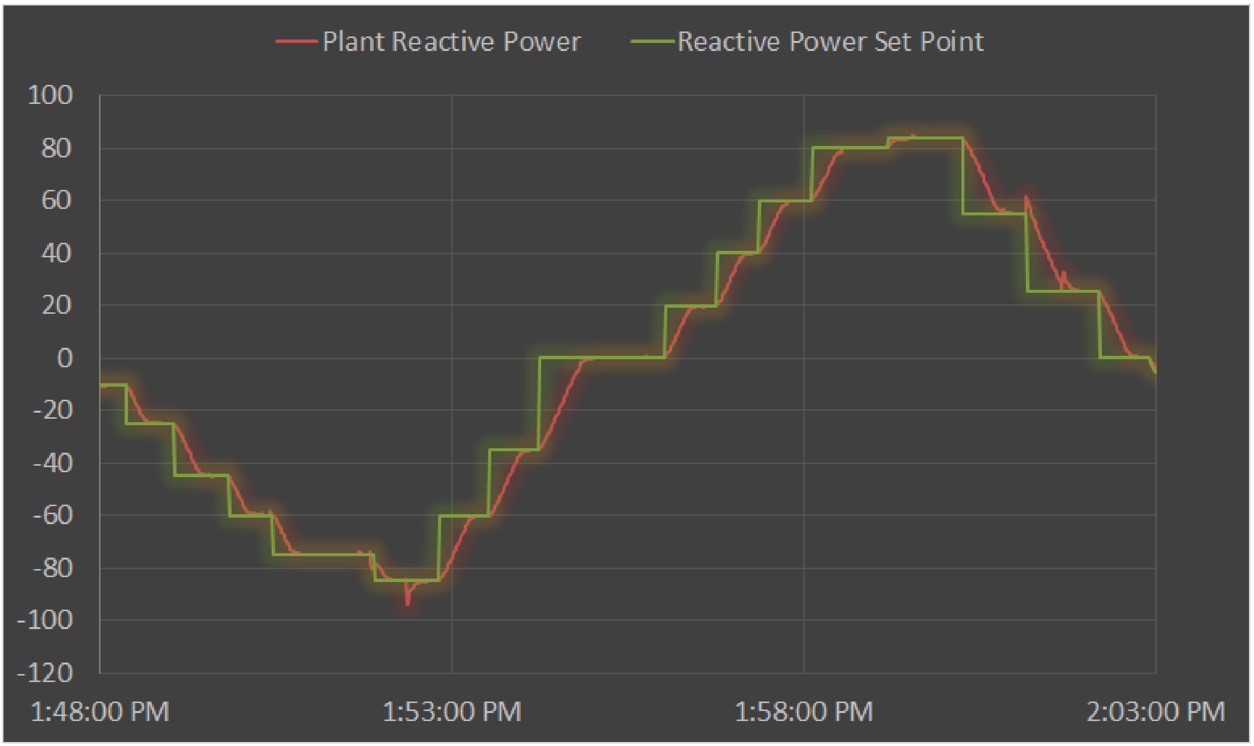


Figure 48. Reactive power control test

5.3 Low Generation Reactive Power Production Test

One way to increase the optimal utilization of PV power plants is to utilize their capability to provide VAR support to the grid during the times when the solar resource is not available. For this purpose, a capability of grid-tie inverters of the 300 MW PV plant to provide reactive power support during no active power generation period was demonstrated. Due to limited time window available for testing it was not possible to test this capability during dark hours of the day. Instead, the team decided to demonstrate the VAR support capability of the plant at nearly zero active power generation. The plant's active output was curtailed to nearly zero MWs on August 24, 2017. Then the command was sent to the plant controller to ramp the reactive power to produce or absorb 100 MVAR. The results of these tests along with measured POI voltage are shown in Figure 49. The plant was fully capable of producing or absorbing the commanded MVAR levels during the whole testing time. It is important to note that the conditions of this test are only partially realistic since special control schemes are needed for grid-tie inverters to operate as STATCOM when PV array is fully de-energized, and certain amount of active power needs to be drawn from the grid to compensate for inverter losses. Such more realistic test for night-time VAR mode is planned for the near future.

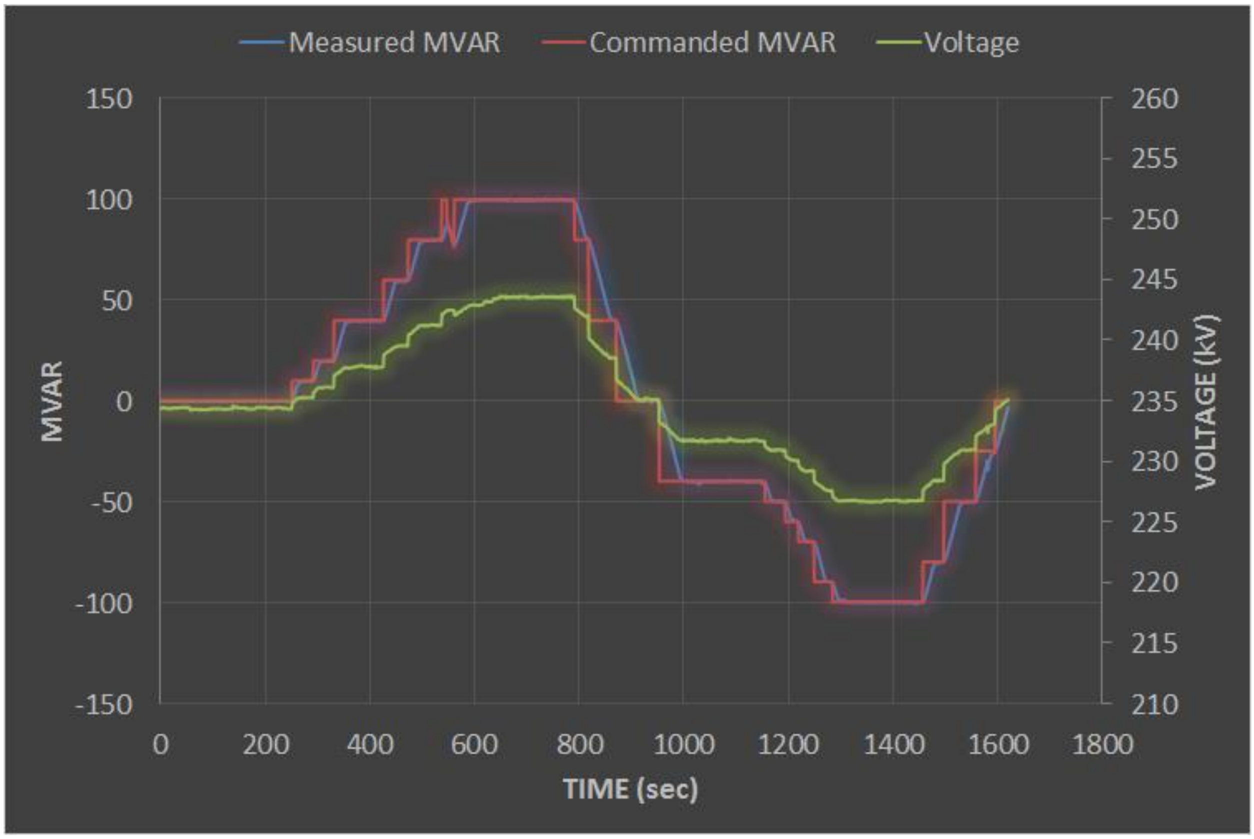


Figure 49. Reactive power production test at no active power (P≈0 MW)

6. Additional Tests

The time series of measured plant active and reactive power and POI voltage for the whole period of testing on August 23, 2016 is shown in Figure 50. This is a summary that combines results of several commissioning tests conducted between 10 am and 3 pm on August 23. The tests conducted in the morning where related to various forms of active power controls, and tests conducted in the afternoon involved various forms of reactive power, voltage and power factor controls.

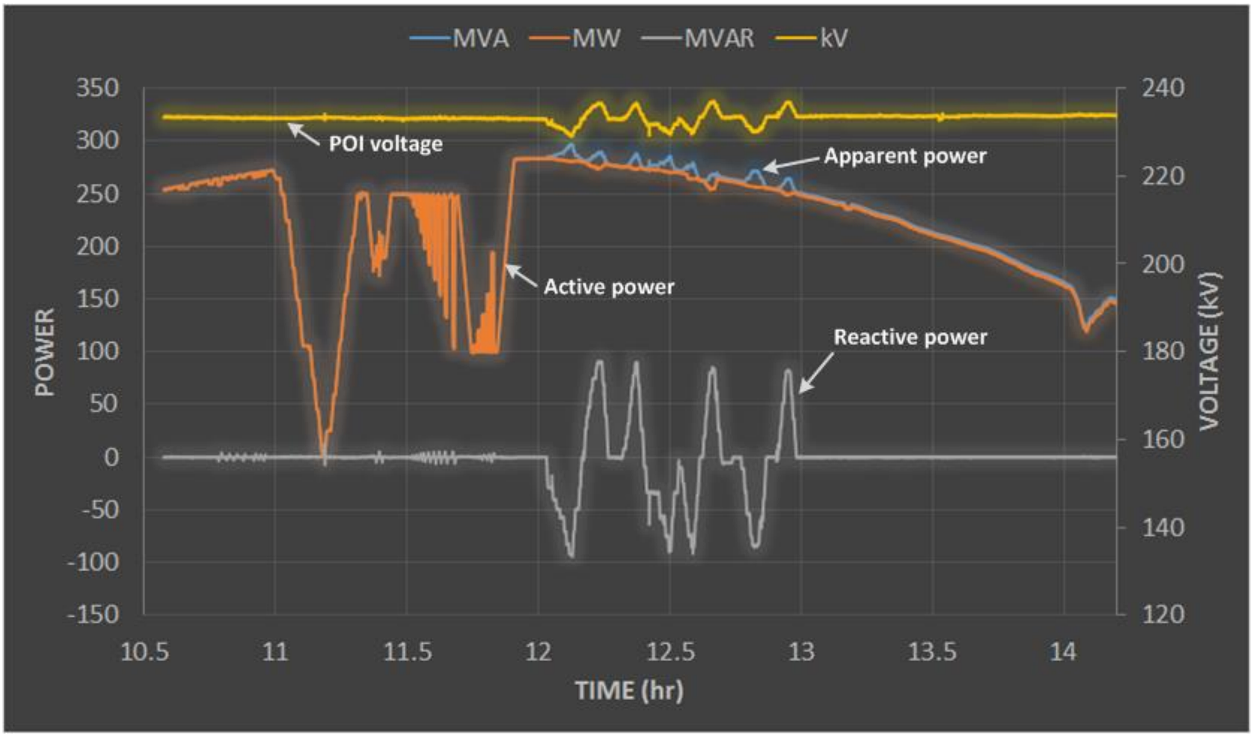


Figure 50: Plant output during Aug 23, 2016 tests

The curtailment control test was conducted to demonstrate the plant's ability to limit its active power production and then restore it to any desired level. The results of the test are shown in Figure 51. The plant was accurately following the active power set point from nearly full production level to zero level with pre-set ramp rate of 30 MW/min. The plant active power was then commanded to increase in accordance to increasing set points. It is important to note that the reactive power of the plant remains unchanged at nearly zero MVAR level for the whole range of active power levels. This is an indicator of the capability to independently control active and reactive power by PV inverters.

The curtailment control test also demonstrates that PV generation can also provide additional ancillary services in the form of spinning and non-spinning reserves. According to the CAISO's definitions, spinning reserve is a standby capacity from generation units already connected or synchronized to the grid and that can deliver their energy in 10 minutes when dispatched. With a demonstrated 30 MW/min ramp rate capability, the PV plant under test is capable of deploying 300 MW of spinning reserve in just 10 minutes for some hypothetical case of full curtailment. Non-spinning reserve is capacity that can be synchronized to the grid and ramped to a specified load within 10 minutes. Similarly, the PV plant can be a provider of non-spinning reserve as well. In fact, in the case of a PV plant, unlike the conventional generation, there is no differentiation between spinning and non-spinning reserve capacity due to the nature of PV generation.

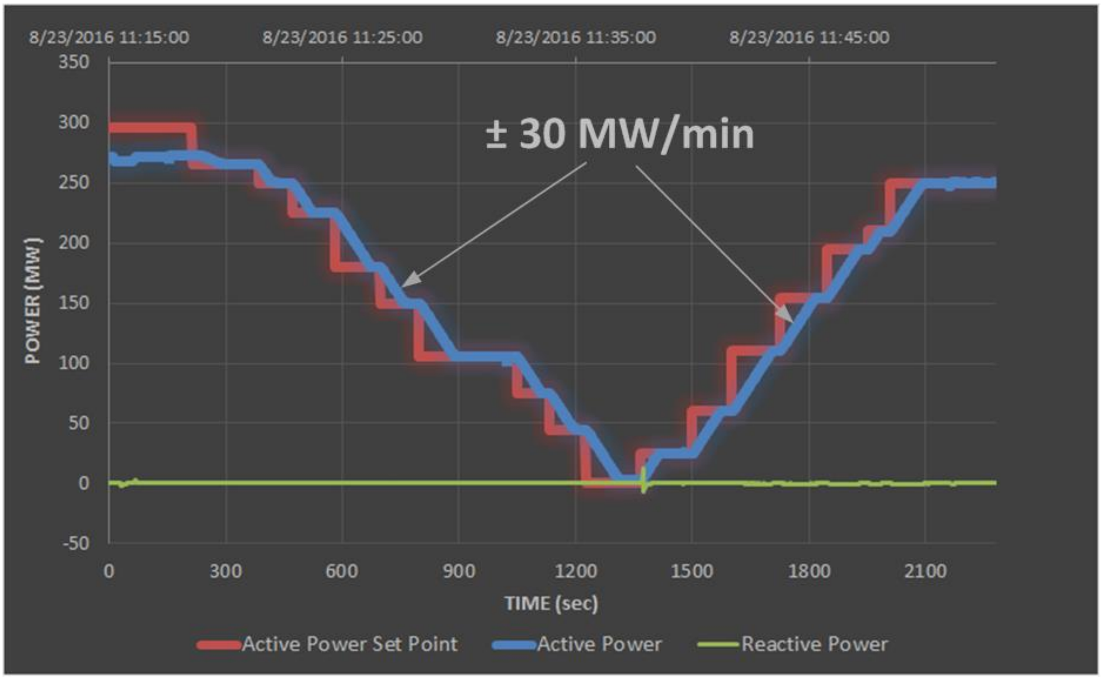


Figure 51: Active power curtailment test

Another type of active power control test, called frequency validation, was conducted to demonstrate the control system response to frequency disturbances. Unlike the frequency droop tests described in Section 4 of this report, the frequency validation tests were conducted with artificially commanded step changes in POI frequency. Figure 52 shows responses of the plant to commanded frequency values. The response of the plant corresponds to 5% frequency droop setting with excellent match between measured and calculated target power levels (all active power ramp rates are bypassed when the plant in frequency regulation mode).

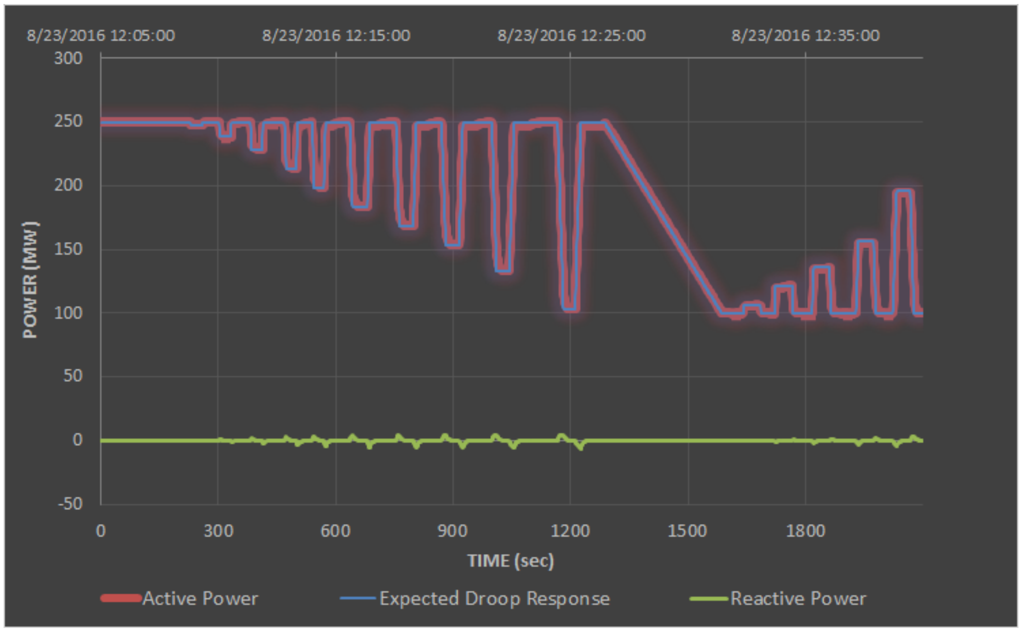


Figure 52. Results of frequency validation test

7. Conclusions and Future Plans

The focus of this project was on demonstrating the controls of a 300 MW utility-scale PV power plant within the CAISO's footprint to provide various types of active and reactive power controls for ancillary services.

Active power control capabilities for inverter-connected plants such as PV power plants have been acknowledged and available for a number of years. However, many of these capabilities have not been proven in a real commercially operational setting by interfacing with the plant operator on the ground as well as the system operator (either utility off-taker or transmission system operator). This project is a result of collaboration between NREL, CAISO, and First Solar. NREL's participation was funded through DOE's Solar Energy Technologies Office. The project team gained valuable real experience for all industry players with (1) the PV power plants' implementations of these capabilities, (2) the system operators' interface and communications acceptance of measured plant parameters and use of the parameters , (3) the iterative loop for the system operators to send back appropriate set points, (4) the logic of the PV power plant controllers to respond to the set points, and (5) the PV power plants' return of up-to-date information (such as available peak plant power) to complete the iterative loop.

The AGC tests demonstrated the plant's ability to follow the CAISO's AGC dispatch signals during three different solar resource intensity timeframes (1) sunrise, (2) middle of the day [noon – 2 p.m.], and (3) sunset. For this purpose the plant was curtailed by 30 MW from its available peak power to have maneuverability to follow the CAISO's AGC signal. During these tests a fast and accurate AGC performance has been demonstrated at different solar resource conditions.

For frequency response tests the plant was also operating in curtailed mode to have enough headroom for increasing its output in response to frequency decline outside of a defined dead band. Headroom is achieved by sending a curtailment command to plant PPC after initially computing its estimation of maximum capability using real-time solar irradiance data from the network of array pyranometers, real-time measurements of panel and inverter data, and other static characteristics of system components. Assuming that the plant will be reimbursed for the energy loss due to curtailment for these ancillary services, the maximum power estimation will likely need to be refined and validated. The plant demonstrated fast and accurate frequency response performance for different droop settings (3% and 5%) under various solar resource conditions for both under and over-frequency events.

The plant also demonstrated the ability to operate in three reactive power control related modes: voltage regulation, power factor regulation and reactive power 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 PV inverters. Also the plant ability to produce or absorb reactive power at nearly zero MW production (STATCOM mode) has been demonstrated as well.

7.1 General Conclusions

General conclusions include the following:

- Advancement in smart inverter technology combined with advanced plant controls allow solar PV resources to provide regulation, voltage support and frequency response during various mode of operations,
- Solar PV resources with this advanced grid-friendly capabilities have unique operating characteristics that can enhance system reliability by providing:
  - Essential reliability services during periods of over-supply,
  - Voltage support when the plant's output is near zero,
  - Fast frequency response (inertia response timeframe),
  - 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 is important for the precision of AGC control. It makes sense to include specifications for such available peak power estimations into 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 utilizing such controls in its operations.
- All hardware components enabling PV power plants to provide a full suite of grid-friendly controls are already in existence in many utility-scale PV plants. It is mainly a matter of activating these controls and/or implementing communications upgrades to fully enable these. 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 implementation of APC capabilities. Modifying programming logic may 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 PV plants. It may be easier with newer equipment because of the faster response times of newer inverters and controller systems.
- Many utility-scale PV power plants 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 (Figure 53**Error! Reference source not found.**).

- Fast response by PV inverters coupled with plant level controls make it possible to develop other advanced controls, such as STATCOM functionality, power oscillation damping controls, sub-synchronous controls oscillations damping and mitigation, active filter operation mode by PV inverters, etc.

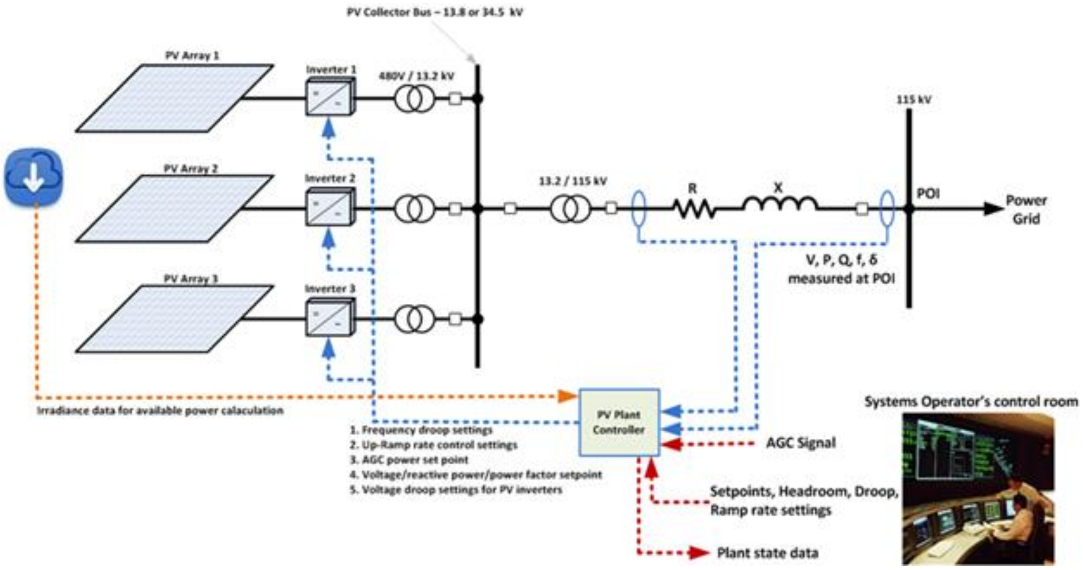


Figure 53. Grid-friendly PV power plant

The project team consisting of experts from CAISO, First Solar and NREL conducted tests that demonstrated how various types of active and reactive power controls can leverage PV generation's value from being a simple intermittent energy resource to a resource providing a wide range of ancillary services. This demonstration on an actual utility-scale operational PV power plant and consecutive dissemination of obtained results, the team will provide valuable real test data to all stakeholders in California and nationwide. If PV-generated power can offer a supportive product that benefits the power system and is economic for PV power plant owners and customers, this functionality should be recognized and encouraged.

With this project's approach to holistic demonstration and dissemination plans, the team sought to close some gaps in perspectives that exist between various stakeholder groups in California and other locations in U.S. by providing real test data from an actual large utility-scale operational PV power plant to all stakeholders.

7.2 Future plans

Future plans by the project team include:

- Identify potential barriers to providing essential reliability services to make these services operationally feasible,

- Explore economic and/or contractual incentives to maximize production and not hold back production to provide reliability services,
- Identify necessary steps to unlock opportunities of using reliability services from renewable resources by:
    1) Assessing and quantifying the fleet's capability to provide reliability services,
    2) Evaluating policies like the FERC NOI (RM16-6) which recommends requiring all synchronous and asynchronous machines to provide primary frequency response,
    3) Considering how renewable resources already dispatched or curtailed down can provide upward regulation and frequency response,
    4) Identifying what tariff changes are necessary to remove barriers and allow VERs to provide reliability services,
    5) Exploring ways to allow invertor based resources and associated control system to be used to enhance reliability and response to frequency events
    6) Exploring further opportunities for inverter based resources to participate in the various markets for energy and ancillary services

- Further modifications in control algorithms and fine-tuning of controls parameters for improved performance of the demonstrated services

- Demonstration of true PV-STATCOM functionality during night-time hours

- Demonstration of ancillary services by a number of PV plants within the CAISO footprint to understand the impacts of solar resource geographical diversity on aggregate response by solar generation on various types of ancillary services

- CAISO and NREL are interested in exploring the possibility of conducting simultaneous demonstration testing of ancillary service controls by solar PV and wind generation to understand the aggregate response by two different renewable energy resources when providing various combinations of ancillary services

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Appendix A: Test Plan

A.1 Objective

Perform multiple tests and document performance of a 300 MW photovoltaic solar facility in a commercially operational setting. The plant currently has a maximum capacity of 299.9 MW and participates in the CAISO's market. The plant is in the process of completing its final acceptance testing in mid to late August.

The CAISO is responsible for ensuring that there are sufficient ancillary services available to maintain the reliability of the grid controlled by the CAISO. Modern utility-scale PV power plants consist of multiple power electronic inverters and can contribute to grid stability and reliability through sophisticated "grid-friendly" controls. The findings of this testing project will provide valuable information to the CAISO concerning the ability of variable energy resources to provide ancillary services, enhance system reliability and participate in future ancillary service markets like traditional generators. All tests would be done in a manner to minimize curtailment to the plant below its current commercial P_{max}. Curtailment details and actual test times would be worked out prior to the tests.

The project team consisting of experts from CAISO, First Solar, and NREL has developed the demonstration concept and test plan to show how various types of active and reactive power controls can leverage PV generation's value from being a simple an intermittent energy resource to providing wide range of ancillary services. Such demonstration and consecutive dissemination of obtained results, the team will provide valuable real test data from an actual utility-scale operational PV power plant to all stakeholders in California and nationwide. If PV-generated power can offer a supportive product that benefits the power system and is economic for PV power plant owners and customers, this functionality should be recognized and encouraged.

A.2 Regulation Up and Regulation Down

This test will demonstrate the plant's ability to follow the CAISO's AGC dispatch signals. The purpose of AGC is to enable the power plant to follow the active power set point dispatched by the CAISO at the end of every 4-sec time interval. The CAISO will conduct the test at three different solar resource intensity timeframes (1) sunrise, (2) middle of the day [Noon – 4 p.m.], and (3) sunset. Each test will provide actual 4-second AGC signals that the CAISO has previously sent to a regulation certified resource of similar size. Normally, the CAISO measures the accuracy of a resource's response to EMS signals during 15 min intervals by calculating the ratio between the sum of total 4-sec setpoint deviations and sum of AGC set points.

(1) Sunrise

During sunrise, the plant would be instructed to operate within a real power range of 20 MW below its peak power capability. About 10-minutes of actual 4-second AGC signals would then be fed into the plant's controller and the plant's response would be monitored.

(2) *Middle of the day*
During the middle of the day, the plant would be instructed to operate within a real power range of 20 MW below its peak power capability. About 20-minutes of actual 4-second AGC signals would then be fed into the plant's controller and the plant's response would be monitored.

(3) *Sunset*
During sunset, the plant would be instructed to operate within a real power range of 20 MW below its peak power capability. About 20-minutes of actual 4-second AGC signals would then be fed into the plant's controller and the plant's response would be monitored.

Expectation

During the test, the 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 MW output changes). The CAISO will also monitor the accuracy of plant's response to the regulation set-point changes. The data from this test will be used by ISO in future resource-specific expected Mileage for purposes of awarding Regulation Up and Regulation Down capacity.

Curtailment
It is expected that the plant would be curtailed by 20 MW for about 45 (3x15 min) minutes.

A3. Voltage Regulation Control

The 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 would be tested to show:

FERC's proposed reactive capability (Order 827), which requires all newly interconnecting non-synchronous generators to design their generating facilities to meet the reactive power requirements at all levels of real power output. (Refer to the vertical red lines in Figure 1.)

Objective

The primary objective of this test is to demonstrate the capability of the plant to operate in the voltage-regulation mode within 0.95 lead/lag 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

The CAISO would test the plant at <u>three</u> different real power output levels. (1) at maximum production during the middle of the day, (2) during sunset when the plant is about 50% of its maximum capability, and (3) during sunset when the plant is close to zero production. The ISO will test the plant reactive power capability to absorb and produce reactive power in accordance to Figure 1, within ±100 MVAR range during various levels of real power output.

- The plant would first be tested at its maximum real power output for a given irradiance level. At maximum real power output, the plant must demonstrate it can produce approximately 33% of real output as dynamic reactive. Similarly, at maximum real power output, the plant must demonstrate it can absorb approximately 33% of its real power output as reactive output.
- During sunset, as the solar production drops off to about 50% of the resource maximum capability, the plant must demonstrate it can produce and absorb approximately 33% of its real power output as dynamic reactive output.
- During sunset, as the plant production approaches zero MW, the plant must demonstrate it can produce and absorb approximately 33% of its real power output as dynamic reactive output.

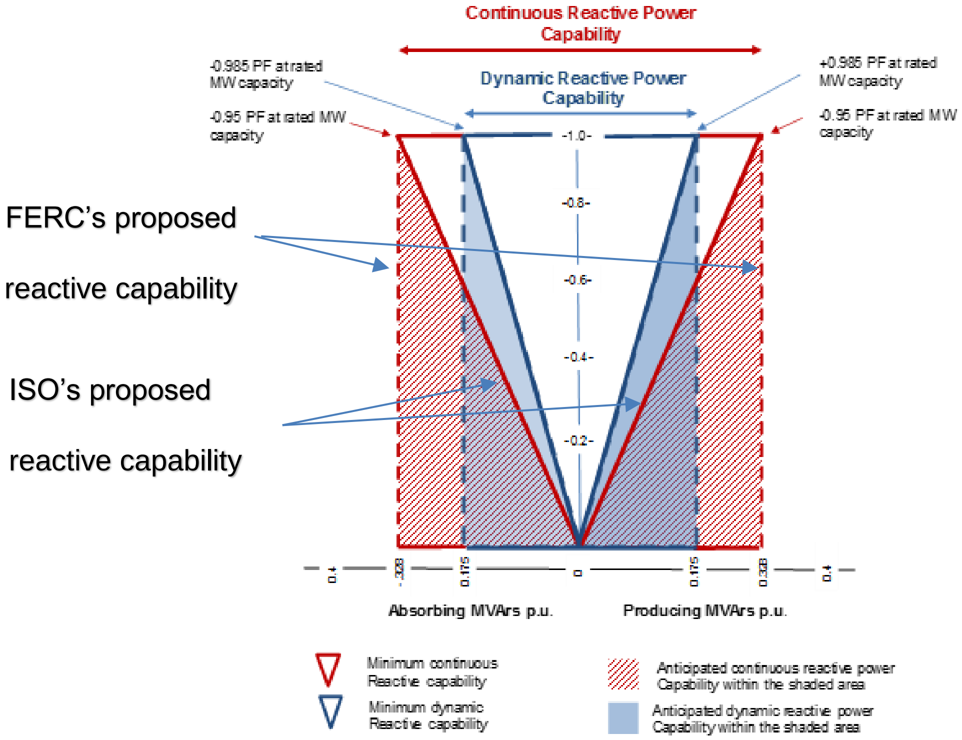

Figure 1: Reactive Power Capability at the POI

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. At all levels of real power output, the plant is expected to produce or absorb reactive power equivalent to approximately 33% of the plant's actual real-power output. For example, at maximum real power capability of the plant, the expected reactive capability should be 33 MVARS lagging or 33 MVARS leading. Also, at zero real power output, the expected dynamic reactive capability should be zero MVARS lagging or zero MVARS leading.

Expectation

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

Curtailment

None

A.4 Active Power Control capabilities

The 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 would be used to determine the plant's ability to provide ancillary services such as spinning reserve and non-spinning 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 would be done at <u>two different ramp rates</u>.

- The plant would be instructed to reduce its output to three different set-points <u>(not to exceed 60 MW)</u> at a predetermined ramp-rate as shown in Figure 2.
- The plant would 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 the above test using a different ramp rate

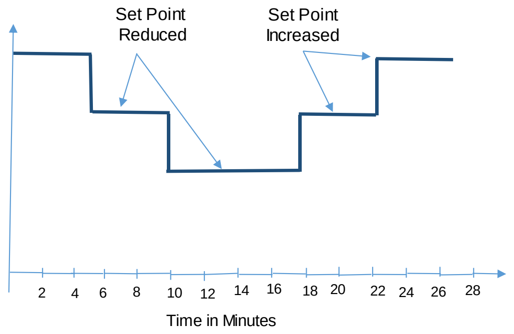

Figure 2: Increase/Decrease Output at a specified ramp rate

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 the plant would be curtailed up to 60 MW for a period of 60 minutes.

A.5 Frequency Response

The frequency response capability would entail two separate test (1) a droop test, and (2) a frequency response test.

The definition of implemented frequency droop control for PV plant is the same as that for conventional generator:

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

The plant rated power (299.9 MW) is used in above equation from droop setting calculation. The plant should adjust its power output in accordance to the droop curve with symmetric deadband shown in Figure 3. The upper limit of the droop curve is the available plant power based on the current level of solar irradiance and panel temperatures.

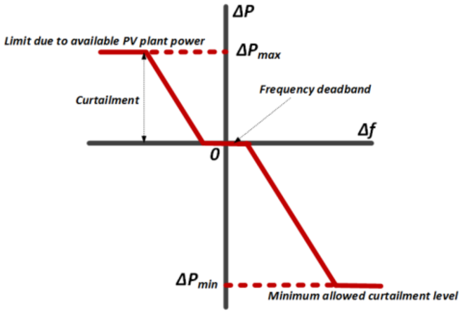

Figure 3: Frequency droop explained

2. *Frequency Droop Test (Capability to provide spinning reserve)*

Objective

The objective of this test is to demonstrate that the plant can provide a response in accordance with 5% and 3% droop settings through its governor-like control system. The plant would be instructed to operate below its maximum capability during both tests.

Test Procedure

For the first test, the plant would be instructed to operate at 20 MW below its maximum capability. This test would be done using a 5% droop and a dead band of ± 0.036 Hz.

- The CAISO would test the frequency droop capability of the plant by using an actual under-frequency events that occurred in the WECC over the past year. The under-frequency event data set (approximately 10 minutes of data) would be fed into the plant’s controller and the plant response would then be monitored.

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

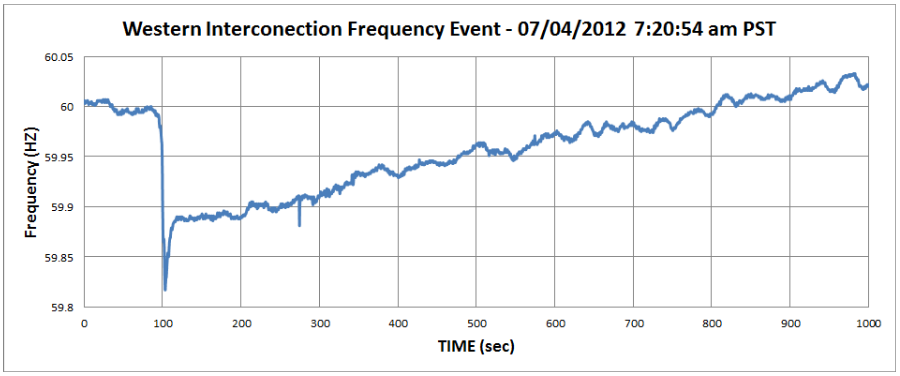

Figure 4: Example under-frequency event

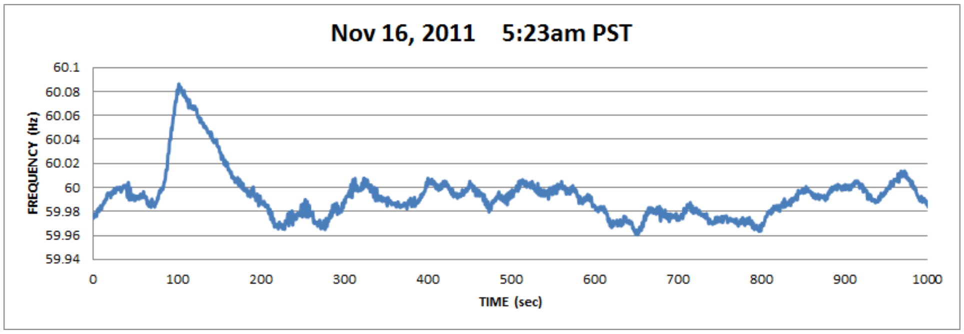

Figure 5: Example over-frequency event

- The frequency event time series data will be used by the power plant controller to trigger the droop response by the plant
- The above test would be repeated with the plant at 20 MW below its maximum capability. This test would be done using a 3% droop and a dead band of ± 0.036 Hz.

Expectation

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

Curtailment

It is expected that the plant would be curtailed by 30 MW for approximately 60 minutes.

3. Capability to provide frequency response

Objective

The objective of this test is to demonstrate that the plant can provide frequency response consistent with NERC's BAL-003-1.

Test Procedure

(1) The plant would 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) would be fed into the plant's controller and the plant's response would be monitored. This test may require tuning a delay in response to ensure the frequency response occurs within 20 to 52 seconds following the step-change in frequency.

(2) The plant does not have headroom and can only reduce output in response to high frequency deviation below scheduled frequency of 0.036 Hz. The test would entail feeding the plant controller with a frequency greater than 0.036 Hz above scheduled frequency.

(3) Repeat the above test with the plant operating at 40 MW below its capability for a given irradiance level.

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 the plant would be curtailed by 20 MW for 60 minutes and 40 MW for 60 minutes.