White Paper – August 2022

California Solar Farm

WECC Generating Facility Data, Testing, and Model Validation

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*Full Appendix to References available upon request

Executive Summary

The objective of this study is to perform a WECC Model validation for a 25 MW client solar farm located in central California . This validation is in accordance with WECC Generating Unit Model Validation Policy [Ref. 1] and WECC Generating Facility Data, Testing and Model Validation Requirements Guideline [Ref. 2]. The validation consists of the following:

•Plant Volt/Var Response to Event
•Plant Dynamic Response to a Frequency Event
•Appendix C. Generating Facility Data Requirements

WECC policy requires the submission of validated generating facility data for all plants connected to the transmission system (60 kV and above) with an aggregate nameplate of 20 MVA or larger at least once every five (5) years. Calculations and analysis provided demonstrate compliance. The field test procedures described in the following sections were conducted at the client solar farm and simulated using the Generic Phase 2 Renewable Energy WECC models.

The following are the results:

Results:

•Plant Volt/Var Response

The recorded reactive power flow data matches with the simulated results. Therefore, the client solar farm plant volt/var response is validated per WECC.

•Plant Dynamic Response to a Frequency Event

The individual SMA America Sunny Central inverters at the client solar farm have 'Active Power Limitation Depending on Power Line Frequency' controls, which limit the active power output when there is an overfrequency condition. However, the facility does not have a plant-level active power/frequency controller. Due to how the plant is controlled, it is impossible to perform a stage test to have the inverters see an overfrequency condition. Adjustments to the inverter settings were implemented as shown in Section 9 to improve the likelihood that the facility would respond to an overfrequency event. At the date of this report, the facility has been monitored for overfrequency conditions for two months with no events reported, so this portion of the model could not be validated at the time of reporting. According to FERC Order 842, 'Essential Reliability Services and the Evolving Bulk-Power System – Primary Frequency Response' issued on February 15th, 2018, the frequency response requirements apply to newly interconnecting generation facilities that execute or request the unexecuting filing of an LGIA or SGIA on or after the rule's effective date as well as to existing large and small generating facilities that take any action that requires the submission of a new interconnection requests that results in the filling of an executed or unexecuted interconnection agreement on or after the effective date.

Background

The intent of this study is to develop test procedures and review the WECC dynamic model and parameters to support the generation model validation at the client solar farm. The validation is in accordance with WECC's Generating Facility Data, Testing and Model Validation Requirements. The purpose of the tests conducted are to confirm the effect of the plant controls and the validation is with respect to active and reactive power injection at the Point of Interconnection (POI) with an emphasis on pre- and post-event levels and recovery dynamics.

- Plant Volt/Var Response to System Event

This baseline validation demonstrates a reasonable match between the WECC approved model and measured data with respect to reactive power response. The dynamic response involves a voltage change of typically 2% or a reactive power change of at least 10% of the plant's rated MVA.

- Plant Dynamic Response to a Frequency Event

This baseline validation demonstrates a reasonable match of the WECC plant controller model with respect to a frequency event. Typically, only an overfrequency response is to be expected for a PV plant. Note, although the client power plant controller does not have active power/frequency control, each individual inverter at the client solar plant has an active power limitation setting that responds to overfrequency events, which provide a similar response to a plant that is controlled by a power plant controller. For more details refer to Section 9.

- Generating Facility Data Requirements

To establish consistent modeling data requirements and reporting procedures for development of planning horizon cases necessary to support analysis of the reliability of the interconnected transmission system.

Input Data: The client solar farm consists of seventeen (17) trackers with each tracker having two (2) 760 kW SMA Sunny Central inverters for a nominal facility power output of 25.84 MW. The plant is rated for 25 MW according to the Interconnection Agreement. The collector system consists of two feeders fed from one collector substation feeder breaker as shown in Drawing E- 1.3.

3.1 Inverter Data

Client solar farm consists of the SMA Sunny Central 760 CP inverters. The steady-state data for these inverters is the following:

- Nominal AC Power: 760 kW @ 0.9 PF (836 kVA)
- Nominal Terminal Voltage: 342 Vac
- Reactive Power Capability Curve: Displacement power factor is 0.9overexcited ….. 0.9underexcited (±365 kVAR)

3.2 Transformer Data

Each set of inverters is connected to the collector system via a Generator Step Up (GSU) transformer with the following parameters:

•Rated Power: 1.5 MVA
•Rated Voltage: 34.5 kV – 342 V – 342 V
•Impedance: 5.75% @ rated MVA & Voltage (assumed X/R =6)
•Connection: 3 Winding Delta, Wye, Wye

The solar farm collector system is connected to MID's 69 kV transmission system via one (1) Main Power Transformer (MPT) with the following parameters per the ABB Power Transformer Performance Specification

•Rated Power: 16.8 MVA / 22.4 / 28 MVA
•Rated Voltage: 69 kV - 34.5 kV
•Impedance: 7.7%, X/R=20.78 @ rated MVA & Voltage
•Connection: Delta, Wye-ground

3.3 System Data & Short Circuit Ratio (SCR)

The maximum fault data at the point of interconnection is based on email correspondence from MID. The minimum fault data at the POI is based on the Overvoltage Analysis prepared in 2019.

Fault Type	Magnitude, X/R
Max Three Phase	13,277 A, X/R =5.23
Min Three Phase	2,765 A, X/R = 5.1
Max Single Phase	13,649 A, X/R = 5.88
Min Single Phase	1,583 A, X/R =6.5

The SCR is the ratio of the short-circuit MVA capacity at the bus in the existing network before the connection of the new generation source and the rated megawatt value of the new connected source as shown in the equation below.

$$SCR = \frac{S_{SCMVA}}{P_{RMW}}$$

The generic dynamic models discussed below are applicable for systems with a Short Circuit Ratio (SCR) of three and higher at the point of interconnection. For the SCR to be greater than 3, the SCMVA needs to be greater than 75 MVA (or ~630 A at 69 kV). As shown in the short circuit data above, the minimum fault current values are above this threshold.

3.4 Plant Level Controller

The plant in this example is controlled using a PID controller that will respond to a voltage disturbance based on the difference between the running average of 'as read' POI voltage and the process variable instantaneous 'as read' POI voltage. During the voltage disturbance, the plant will respond by adjusting its reactive power output based on the amount and duration of the voltage deviation.

3.5 Dynamic Model

The initial PSLF dynamic model developed for the plant used the ‘wt4g’ and the ‘wt4e’ models. However, according to the 2018 WECC Approved Dynamic Model Library [Ref. 3] these models should be transitioned to the new Phase II REGC_A model and the REEC_A or REEC_B (A to be used if momentary cessation is considered). Additionally, there is a power plant controller model that can be used, REPC_A. Note, these generic models are applicable for systems with a Short Circuit Ratio (SCR) of three and higher at the point of interconnection and are not intended for studying parts of the system with very low short circuit levels.

•REGC_A: Generator/convertor (inverter) model reconciles the current commands with the boundary conditions to yield current injections
•REEC_B: Electrical control model translates real and reactive power references into current commands
•REPC_A: Plant controller takes values from the network solution and produces real and reactive power references

Methodology

To support the verification of the plant’s volt/var control functions and active power/frequency control function per the WECC Generating Unit Model Validation Policy, the following steps are required:

•Develop a computer model with dynamic capabilities. The computer model is developed based on the discussion in Section 5 below.

•Develop test procedures for the staged tests which demonstrate:

- The plant’s volt/var response at the POI due to a system voltage or reactive power change

- The plant’s active power/frequency response at the POI due to a system frequency change. Note, the client power plant controller does not have active power/frequency control. However, each individual inverter at the client solar plant has an active power limitation setting that responds to overfrequency events, which provides a similar response to a plant that is controlled by a power plant controller. For more details refer to Section 9.

•Perform the stage tests in accordance with the developed test procedures
•Validate the computer model by comparing the results from the simulation against the stage tests. The models are validated once the simulation results closely match the stage event results.
•Summarize plant data to support analysis of the reliability of the interconnected transmission system.

Computer Model Development

A computer model of the collector system is required to support the model validation. This model requires steady-state electrical parameters for the solar inverters, GSU transformers, collector system cable impedances and susceptances, main substation transformer, and any overhead or underground transmission line connecting the facility to the point of interconnection (POI). Along with the steady-state electrical parameters, a dynamic model of the solar inverters is required to be developed.

5.1 Steady-State Collector System Electrical Parameters

The collector system is modeled based on an equivalent circuit representing each feeder. This simplified equivalent representation of the collector system steady-state electrical parameters for inverter-based resources is shown below.

Impedance

The circuit shown below represents the parallel and series combination of several feeders at the 34.5kV collector system.

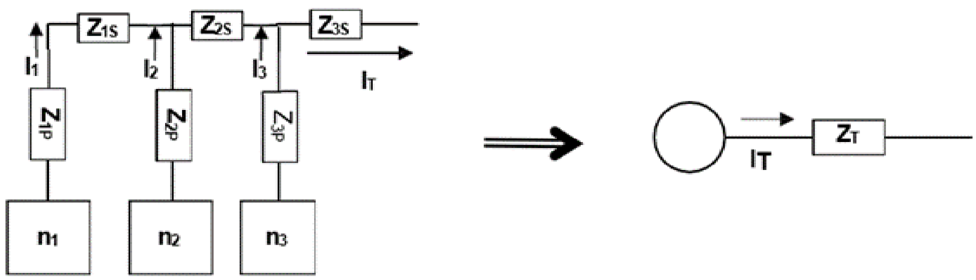

Figure 1 Equivalent System Representation of a String of Solar PV Inverters

$$Z_T = \frac{\sum_{i=1}^{np} n_i^2 Z_{iP} + \sum_{i=1}^{ns} \left(\sum_{j=1}^{i} n_j\right)^2 Z_{iS}}{\left(\sum_{i=1}^{np} n_i\right)^2}$$

Where Z_T is the total impedance of the cables connected to wind turbines in a group

ns is the number of series cables in a group

np is the number of parallel cables in a group

Shunt (Susceptance) Representation

The circuit shown below shows the shunt susceptance of a feeder circuit at the 34.5 kV collector system.

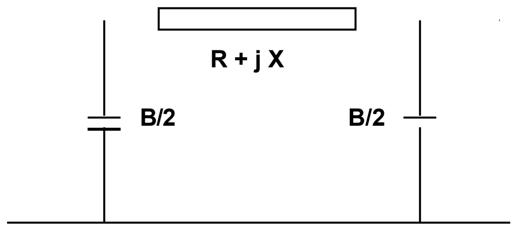

Figure 2 Equivalent Shunt Representation of a String of Solar PV Inverters

The total shunt susceptance (i.e., capacitance) within the solar PV plant is calculated as follows:

$$\boldsymbol{B_T} = \sum_{i=1}^{n} \boldsymbol{B_i}$$

Where $\boldsymbol{B_i}$ is the capacitive susceptance of the collector system to each solar PV inverter

n is the total number of solar PV inverters grouped together

Equivalent Pad Mount Transformer Representation

The pad mount step-up transformer is represented to process the entire string of solar PV inverters as explained below. The equivalent circuit is scaled so that the resulting voltage drop across the (leakage) impedances, and the reactive and real power losses are equal to the sum of individual reactive and real losses of the turbines.

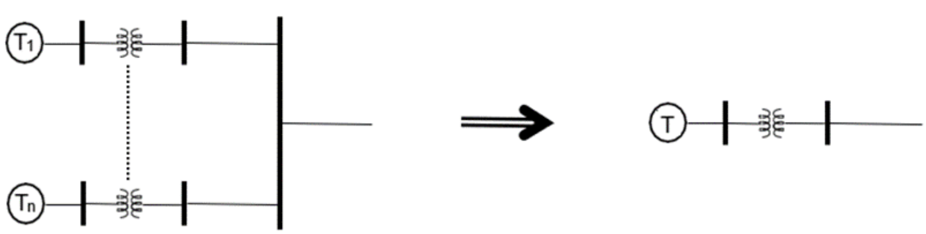

Figure 3 Equivalent Transformer Representation of a String of Solar PV Inverters

The rating of the equivalent pad mount transformer is,

$$S_{t\_eq} = \sum_{i=1}^{n} S_{ti}$$

The impedance of the equivalent transformer in per unit is same as the impedance of individual transformer in per unit.

Calculated Steady-State Model Parameters

The client solar farm collector system is modeled as shown in Figure 4. The equivalent parameters are summarized below with more details shown in Appendix D.

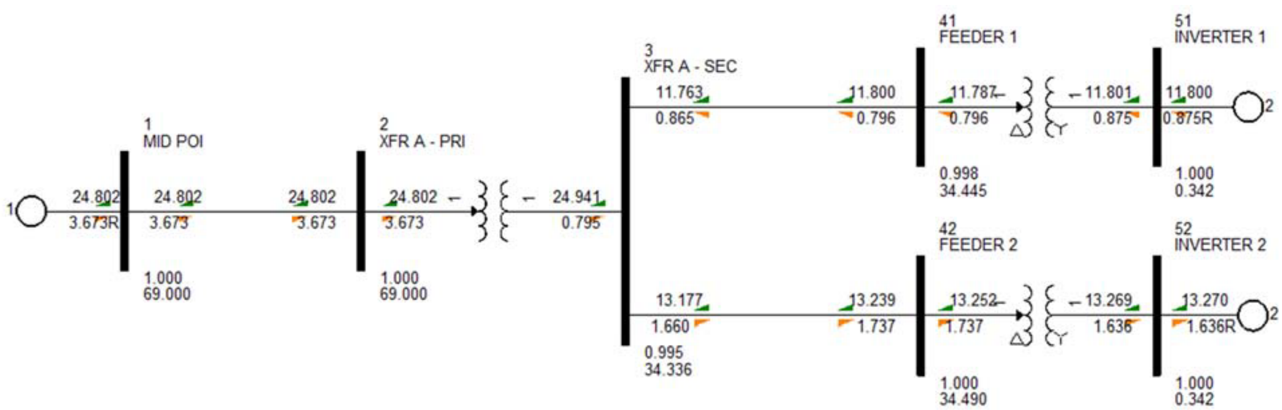

Figure 4: Client Solar Farm Equivalent Model

Table 1 Client Solar Farm Steady-State Electrical Model Parameters

Feeder	Generator Equivalent			Step Up Transformer Equivalent		Collector System Equivalent*		
	Pmax (MW)	Qmin (MVAR)	Qmax (MVAR)	MVA Rating	Z (%)	Req (pu)	jXeq (pu)	jBeq (pu)
1	12.16	-5.84	5.84	12	5.75	0.02631	0.00674	0.00079
2	13.68	-6.57	6.57	13.5	5.75	0.03479	0.00876	0.00093

*Per unit based on 100 MVA and 34.5 kV base

5.2 Dynamic Parameters

The WECC approved dynamic files for inverter-based resources are used and adjusted, if necessary, to provide an accurate response of the solar PV plant’s dynamic behavior. The solar PV inverters are modeled as one equivalent inverter per feeder. The equivalent parameters are identified in Table 1 above. The models used for the equivalent solar PV inverters are the following:

•REGC_A: Generator/convertor (inverter) model reconciles the current commands with the boundary conditions to yield current injections
•REEC_B: Electrical control model translates real and reactive power references into current commands
•REPC_A: Plant controller takes values from the network solution and produces real and reactive power references

WECC Generating Unit Model Validation Policy

Standard

Accurate models of generators and associated controls are necessary for realistic simulations of the electric power system of the western interconnection. Baseline testing and periodic performance validation are required to ensure the dynamic models and databases that are used in the grid simulations are accurate and up to date. This policy statement applies to all plants connected to the transmission system (60 kV and above) with an aggregate nameplate of 20 MVA or larger at least once every five (5) years.

Effective Dates

Approved by the Board at the meeting September 6, 2012

Generator Owner Responsibilities

1. Generating Facility Data
    a. Generator owner shall provide to the Transmission Planner the information for the Generating Facility as specified in the *Generating Facility Data Requirements* [Ref. 2, Appendix C].
    b. Generator owner shall review, verify, and update the Generating Facility data when any of the following conditions occur:
        i. No later than 180 days after the New Generating Facility is released for Commercial Operation.
        ii. No later than 180 days after existing generating unit re-starts commercial operation with modified equipment that influences the behavior of the plant.
        iii. At least once every five years.

2. Baseline Testing
    a. The Generator Owner shall test the generating unit and validate its model data and shall provide these reports to its transmission planner. Refer to *Generating Unit Baseline Test Requirements* [Ref. 2, Appendix B] document for more information.
    b. Testing and associated validation by simulation shall be performed on a generating unit when any of the following conditions have occurred:
        i. If generating project has not been certified by WECC under Generating Program since January 1997.
        ii. No later than 180 days after the New Generating Facility is released for Commercial Operation.
        iii. No later than 180 days after existing generating unit re-starts commercial operation with modified equipment that influences the behavior of the plant.
        iv. No later than 180 days after Generator Owner is notified by WECC of inadequate model response to actual response.
        v. Generator Owner shall notify Transmission Planner when generating unit re-testing and validation are required to maintain compliance with this policy.

1. Model Data Validation
    a. The Generator Owner shall perform model data validation for all units and provide a report to its Transmission Planner at least once every five years.
        i. The Generator Owner shall notify the Transmission Planner when their generating unit re-testing and validation are required to maintain compliance with this policy.
        ii. The "Generating Facility Model Data Validation Requirements" [Ref. 2] document describes acceptable methods of model data validation by performance comparison.
    b. Generator Owner shall verify that generator control limiters, protection and equipment capabilities are consistent with those reported in the model(s).

Testing

Dynamic model verification activities focus primarily on the plant-level controller and the aggregate performance of the electrical controls of the individual units. Dynamic model verification can be performed using either 'Disturbance-Based Model Verification' or 'Staged Testing'. Measured events from disturbances were not available for the client solar farm so the following staged tests are performed using the methodology described below. This methodology is based on Appendix B, Item 6 of WECC Generating Facility Data, Testing and Model Validation Requirements guideline [Ref. 2] and the NERC Power Plant Model Verification for Inverter-Based Resources reliability guideline [Ref. 6].

7.1 Baseline Type Validation for PV Inverter Models

a) Validation of the model provided to WECC will be against reference data. This reference data can be factory tests, field tests, field disturbances, or simulated response obtained from manufacturer-validated reference models. The baseline tests were done at the factory and are not included in this report.
b) The validation will be with respect to active and reactive power injection at the machine terminals, with emphasis on steady-state levels pre and post event, as well as post-event recovery dynamics.

Note, this baseline model validation was done during the commissioning of the plant back in August and November of 2012 and is not included in this report.

7.2 Plant-level Baseline Tests to Confirm the Effect of Plant Controls

a) Validation will be with respect to active and reactive power injection at the Point of Interconnection (POI), with emphasis on pre and post event levels, and recovery dynamics. Validation will be demonstrated for the following two output ranges of the plant: (1) 40% to 60% of rated MW output (2) 75% to 100% of rated MW output.

a. Plant Volt/Var response to system event will demonstrate reasonable match between the WECC approved model and measured data with respect to reactive power response. The dynamic response test will involve a voltage change of at least 2% or reactive power change of at least 10% rated MVA. See Section 8 for the testing procedure.

o Dynamic Response to a frequency event should demonstrate a reasonable match of the WECC plant controller model with respect to a frequency event. Over- frequency event will be used for the PV plant.

Volt/Var Response Test Procedure

Objective: Demonstrate plant volt/var response is a reasonable match between the WECC approved model and measured (or stage test) data with respect to reactive power response. For inverter-bases resources, the volt/var control typically operates in one of the following operating modes: voltage control, power factor control, or constant var control, and these are typically controlled at the Point of Interconnection (POI) using a plant-level controller (modeled using REPC_B models).

General Requirements: The test should be performed with at least 90 percent of the PV inverters on-line. If this cannot be accomplished at time of initial test, document the reasons why and test to its full capability at the time of the test. The test should be rescheduled within six months of being able to reach 90 percent threshold. The dynamic response should involve a voltage change of at least 2% or a reactive power change of at least 10% rated MVA.

Precautions: During the test, the voltages at the POI should be measured and should remain within acceptable limits.

Procedure: The following procedure should be followed to validate the Volt/Var response of the facility.

1) Record the start and end time of the test

2) List the voltage schedule provided by the Transmission Operator, if applicable, or if they maintain a specific voltage.

3) Identify and document the location where the measurements will be performed. This is usually at the Point of Interconnection (POI).

4) Identify and record the initial operating conditions (Voltage, MW, MVAR, PF) at the POI. This is known as the "Initial Operating Conditions" for this test procedure. Based on historical data for this facility, initial operating voltage is typically around 1.03 pu of the nominal system voltage.

5) Adjust the voltage setpoints for the plant by setting an internal control point within the SunPower / SMA inverter control system ensuring that the voltages at the POI do not exceed the acceptable limits (0.95 to 1.05 pu of Nominal System Voltage). Setpoints considered are voltage setpoints that result in the following. Wait 30 minutes between adjustments.

   a. Set at +5% bias of operating voltage, -5% bias of operating voltage, & nominal voltage

6) For each setpoint change, record the voltage, real power, reactive power, and PF at the POI. Additionally, if measurements are available, record the voltage, real power, reactive power and PF at the secondary of the main substation transformer. Data should be tabulated using a minimum of 1 sample per second

and it is recommended to allow a minimum of 3 minutes between each setpoint change. See Appendix B for a sample of the data.

Metering: Based on historical testing for this facility, the 69 kV SEL-751 relay and the 34.5 kV SEL-735 meter will capture the necessary information required to validate the WECC models.

MID will also provide back-up recorded response data (i.e. MW, MVAR, Frequency, and Voltage), that will be recorded at a two second scan rate from its EMS/SCADA system.

Active Power/Frequency Response Test Procedure

Objective: Demonstrate plant dynamic response to a frequency is a reasonable match between the WECC approved model and measured (or stage test) data with respect to a frequency event. Over-frequency event will be used for the PV plants.

General Requirements: The test should be performed with at least 90 percent of the PV inverters on-line. If this cannot be accomplished at time of initial test, document the reasons why and test to its full capability at the time of the test. The test should be rescheduled within six months of being able to reach 90 percent threshold.

Precautions: Conducting tests should consider that there is the potential for the active power to be dynamic due to the constant changes is solar irradiance at any given time. When the input energy source changes, this causes a natural change in active power output of the facility which is not accounted for in the simulation. If the change is output cause by external factors is too large relative to the change in output caused by the test, then the signal to noise ratio is too small and the test cannot be used for verification purposes. This is of particular concern when the test is over a relatively long duration on the order of tens to hundreds of seconds.

Procedure: The following procedure should be followed to validate the active power/frequency response. Note, since it is not possible to adjust the system power frequency to obtain a response based on how the plant is controlled, it was discussed to adjust the inverter settings to make them more sensitive to real overfrequency conditions.

1) Adjust the 'Active Power Limitation Depending on Power Line Frequency' setting for the Sunny Central inverters.

    a. Based on the 'Active Power Limitation Depending on Power Line Frequency' setting for the Sunny Central inverters, the active power will be reduced for each inverter based on the following equation (See Section 6.1.9 of Sunny Central Operating Manual).

$$\boldsymbol{Plim} = \boldsymbol{Pcur} - ((\boldsymbol{fgrid} - \boldsymbol{PHzStr}) \times \boldsymbol{PWGra} \times \boldsymbol{Pcur})$$

Where,

Plim = power limit Pcur = current power

Fgrid = power line frequency

PHzStr = selected frequency limit which will lead to reduction of

feed-in power (existing setting = 60.2 Hz)

PWGra = gradient for reducing active power (existing setting =

40%/H)

b. Change the following settings to increase the sensitivity of the active power regulation.

Settings	Existing Value	New Value
PHzStr	60.2 Hz	60.07 Hz
P-WGra	40 %/Hz	80 %/Hz

For example, if each inverter was outputting 675 kW and an overfrequency condition of 60.1 Hz was sustained, the power of each inverter would be limited to
675 kW – ((60.1 Hz – 60.07 Hz) * 80 %/Hz * 675 kW) = 658.8 kW
This corresponds to an overall plant reduction of, 34 Inverters x (675 kW – 658.8 kW) = 550.8 kW

2) Install measuring device that will trigger during an overfrequency event. Based on MID's review of historical data, there is a high probability that the system frequency will reach above 60.07 Hz for a duration of a few minutes or more.

3) For the event, record the voltage, real power, reactive power, and PF at the POI. Additionally, if measurements are available, record the voltage, real power, reactive power, and PF at the secondary of the main substation transformer. See Appendix C for a sample of the data.

Test Data & Results

The following figures illustrate the response of the client solar farm during the tests performed as well as a comparison of the test results to the computer model. The details of the computer model are shown in Appendix C and D.

1.1 Volt/Var Response

On June 25th, 2019, a voltage test related to the volt/var WECC Model validation was conducted at the client Solar farm. The test was performed with the facility operating near 100% of rated nameplate MW output as well as at 50% of rated MW. The recorded reactive power flow VARs is shown in the plot below:

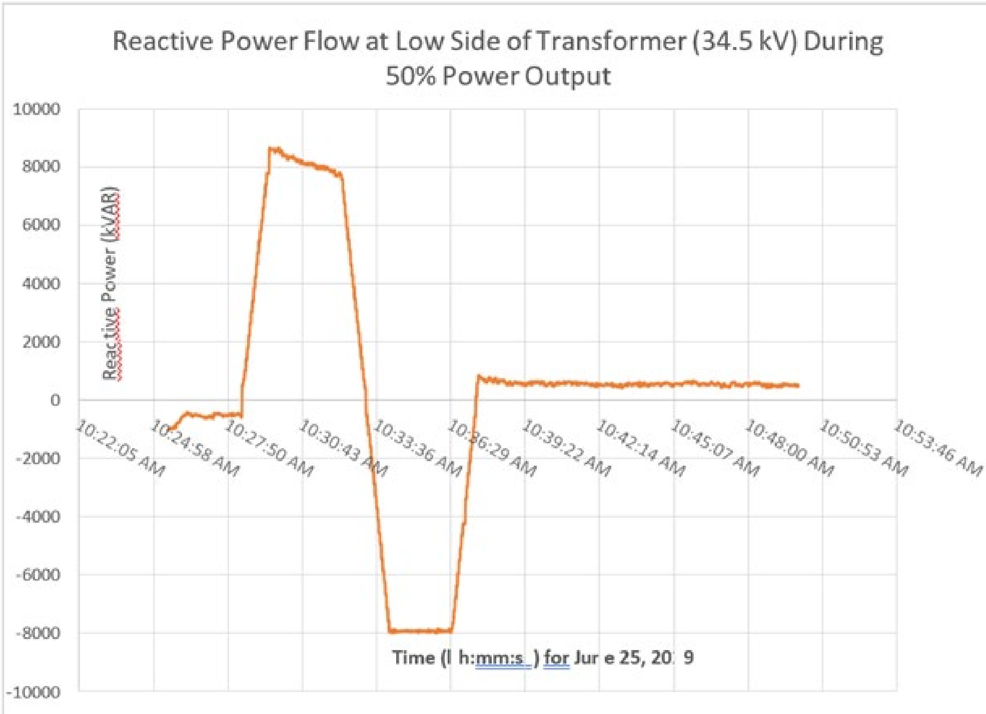

Figure 6: Recorded Reactive Power Flow During Test at 50% Power Output

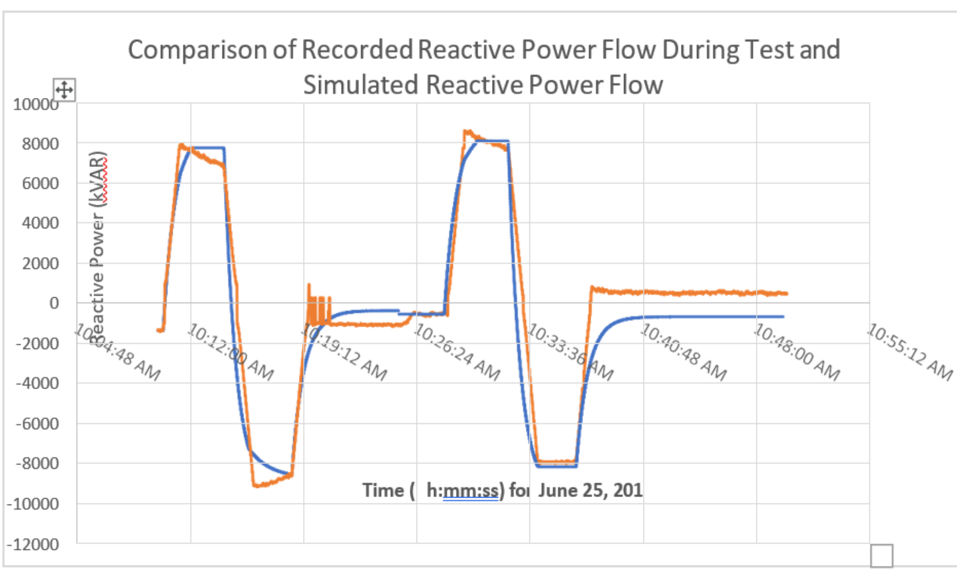

Figure 7: Comparison of Recorded Event Data with Simulation Results

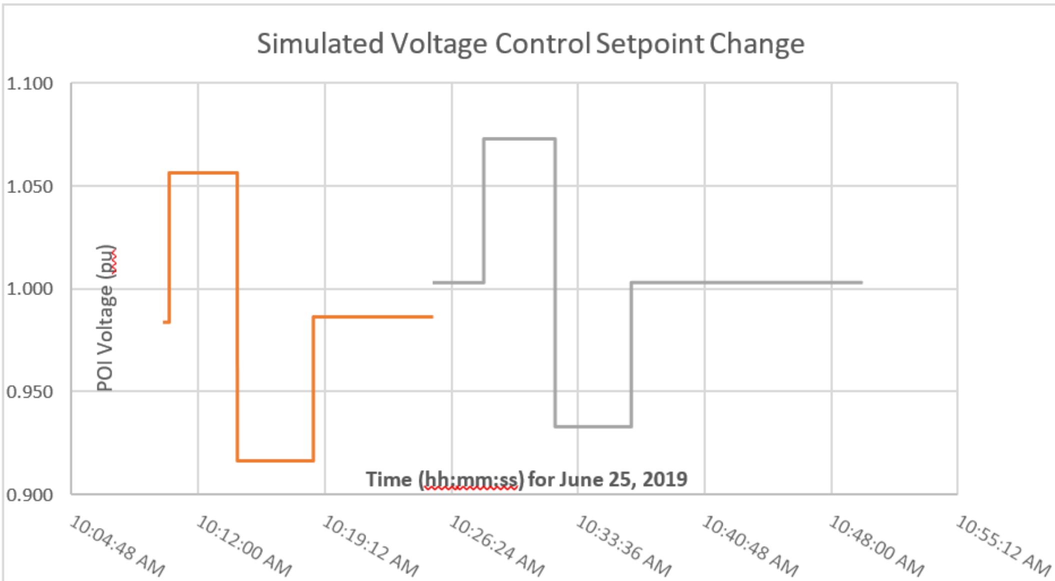

Figure 8: Simulated Setpoint Changes

10.2 Active Frequency Response

The individual SMA America Sunny Central inverters at the client solar farm have 'Active Power Limitation Depending on Power Line Frequency' controls which limit the active power output when there is an over frequency condition, however, the facility does not have a plant level active power/frequency controller. Due to the way the plant is controlled, it is not possible to perform a stage test to have the inverters see an 'overfrequency' condition. Adjustments to the inverter settings were implemented as shown in Section 9 to improve the likelihood that the facility would respond to an overfrequency event. At the date of this report, the facility has been monitored for overfrequency conditions for two months with no events reported so this portion of the model could not be validated at this time. According to FERC Order 842, 'Essential Reliability Services and the Evolving Bulk-Power System – Primary Frequency Response' issued on February 15th, 2018, the frequency response requirements apply to newly interconnecting generation facilities that execute, or request the unexecuting filing of an LGIA or SGIA on or after the rule's effective date, as well as to existing large and small generating facilities that take any action that requires the submission of a new interconnection requests that results in the filling of an executed or unexecuted interconnection agreement on or after the effective date.

References

1. WECC Policy: "Generating Unit Model Validation", September 2012
2. WECC Guideline: "Generating Facility Data, Testing and Model Validation Requirements", October 2012
3. WECC Approved Dynamic Model Library, Version May 2018: Effective date is 5/11/18
4. WECC Guideline: "Solar Plant Dynamic Modeling Guidelines", May 2014
5. WECC Guideline: "Central Station Photovoltaic Power Plant Model Validation Guideline", March 2015
6. NERC Reliability Guideline: "Power Plant Model Verification for Inverter-Based Resources", September 2018.
7. Dwg. No. E-1.2, Rev. 0 "Client Solar Farm – Collector Substation Protection Schematic Drawing" (Attached)
8. Dwg. No. E-1.3, Rev. 1, "Client Solar Farm – Electrical 34.5kV Collector Circuit Single Line Diagram" (Attached)
9. ABB Certified Transformer Test Report for GSU (Attached)
10. SMA America Sunny Central Reactive Power Capability Curves (Attached)
11. Email from Client Representative (Client) to Client, "Over frequency droop response at Client site", dated June 18, 2013 (Attached)
12. 'Local' Irrigation District (SG) – Client Grid Controller – Voltage Response Logic (Attached)
13. Client Documentation: "Utilization of Generic Models for Simulation of SMA Sunny Central Three-Phase Solar Inverters for Power Flow and Stability Studies", Rev. 07, August 21, 2018 (Attached).
14. Email from Client (client) to Craig Starr (EPS), "5-Years Model Validation – (Undisclosed) Solar – Align Expectations", dated January 3rd, 2019 3:02 PM (Attached)