Grid Integration of Large Utility-Scale PV Plants: Key Lessons Learned

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Abstract

The increase in competitiveness of PV-generated electricity has resulted in a dramatic growth in both the number and the size of utility-scale PV plants on the power grid. The impact of PV generation on grid reliability and stability is becoming increasing critical; especially as the solar generation grows to become a significant contributor to the grid. In this paper, we describe some of the key lessons that we have learned in deploying large utility-scale PV plants of hundreds of MW in size. These include development of “grid friendly” features such as plant-level voltage regulation, active power controls, ramp-rate controls, fault ride-through, frequency control and others. Also, we address the need for accurate modeling of the PV plant to facilitate power systems planning. We use actual field data from First Solar-developed PV plants to illustrate these concepts. We conclude with an insight on how grid operators are leveraging the newly developed PV plant capabilities to support the transmission grid during abnormal conditions grids.

Introduction

The impact of integrating rapidly growing PV generation on power systems especially as it relates to grid reliability and stability can be broadly categorized into three areas based on the time scale of grid operation. The first is related to the PV plant’s response to grid disturbances on sub-seconds to minutes time scale. Unlike the inherent electromechanical dynamics of synchronous generation, PV generation response based on power electronics is quite different. The second is related to load balancing which is of the order of sub-hours to days. The third is related to power systems planning which is of the order of years to decades. The impact of PV on each of these categories is different and should be addressed accordingly.

Figure 1 Grid Integration Categories

A. Grid Controls – Grid Stability and Reliability

A task force under the aegis of the North American Electric Reliability Corporation (NERC) has made several recommendations on specific requirements that such variable generation plants must meet in order to provide their share of grid support (Piwko, et al., March 2012). 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. These recommendations are not mandatory in many jurisdictions. However, we have learned that incorporating these recommendations does contribute actively to grid stability and reliability.

B. Scheduling -- Load Balancing

Another grid integration concern, especially for a grid operator, is scheduling generation sources to achieve the require load balancing. Solar generation is a type of variable power generation that is not fully dispatchable, since the energy source is influenced by the presence of solar radiation and by atmospheric conditions. Reliable power-system operation requires the continuous balance of supply and demand. To successfully manage a variable generation source like solar, grid operators treat PV generation as “negative” load and they utilize short-term forecasts to schedule and dispatch compensatory controllable resources . The operators are already familiar with a certain amount of variability and uncertainty, particularly with system load (or demand). They have successfully utilized a variety of tools such as generator and transmission flexibility, ancillary services, and demand-side resources to achieve reliable system operation. The growing sophistication and accuracy of short-term solar generation forecasts is facilitating efficient and reliable system operations (Lauby, et al., 2011). Another key lesson is that by ensuring that PV generation supports forecasting needs of grid operators, this variable source can address the load balancing needs of grid operators. The short-term forecast capability is readily available for most utility-scale PV plants. An advantage of solar in many markets is that its peak generation coincides with higher load demand, making it more a valuable generation resource.

C. Grid Flexibility and Power Systems Resource Planning

An important element of power systems planning is the use of plant models to perform load flow analysis and dynamic system studies. Another key lesson we have learned is that it is critical to provide plant models that accurately reflect the plant performance for such studies as part of the utility-scale PV plant development.

As the proportion of variable generation increases in the overall generation portfolio, another integration concern is that greater grid flexibility is required to provide the necessary power backup when the variable generation resource is not adequate to meet the demand. This dictates increased use of conventional resources that are able to respond and ramp up more quickly, and reduced use of inflexible generation resources. For example, in California, the CAISO team has already recognized this need for such grid flexibility and is developing markets for such flexibility (C.Lyton, 2013). Also, recent analysis point out “that planning the lowest-cost, lowest-risk investment route aligns with a low-carbon future. From a risk management standpoint, diversifying utility portfolios today by expanding investment in clean energy and energy efficiency makes sense regardless of how and when carbon controls come into play. Placing too many bets on the conventional basket of generation technologies is the highest risk route” (Binz, 2012).

Grid Friendly PV Plant

A typical utility-scale PV solar generation plant is composed of multiple individual “generators” connected to the electrical network via power electronics (inverters), rather than synchronous machines. The PV plant’s response to grid system disturbances is not similar to the inherent electromechanical dynamics of synchronous machines. A plant-level controller that is designed to make the PV plant behave as a single large generator is able to contribute actively to grid stability and reliability and operate effectively in the grid. The controller coordinates each individual inverter’s output to regulate the total plant’s real and reactive power output or voltage (Morjaria, et al., 2014).

A grid-friendly PV plant provides the following plant-level control functions:

- Dynamic voltage and/or power factor regulation of the solar plant at the point of interconnection (POI)
- Real power output curtailment of the solar 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 to lower plant output in case of over-frequency situation or increase plant output (if possible) in case of under-frequency
- Start-up and shut-down control

PV Plant Controller

The plant controller 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 rapid response to commands from the plant controller.

Figure 2 illustrates a block-diagram overview of the control system and its interfaces to other devices in the plant. The power plant controller 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 settings at the POI.

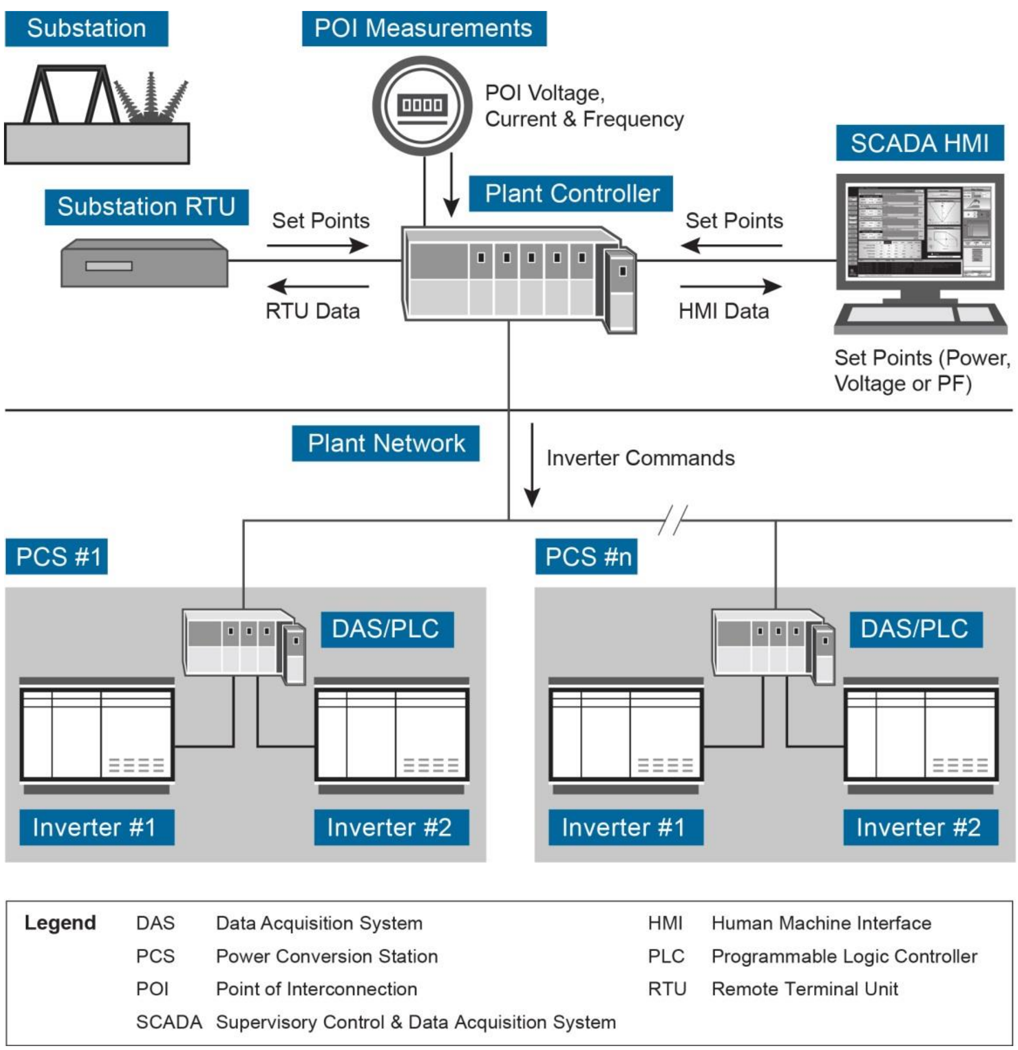

Figure 2 Plant Control System and Interfaces to Other Components

The plant operator can provide the desired settings to the controller through a SCADA HMI screen. In the case of power curtailment command, when the control system detects that the active power at POI exceeds the specified set point, it calculates and sends the commands for each inverter individually to lower its output to achieve the desired set point, using a closed-loop control mechanism. The plant controller also dynamically stops and starts inverters as needed to manage the specified active power output limit when necessary. It also ensures that the plant output does not exceed the desired ramp rates, to the extent possible. It cannot, however, always accommodate rapid reduction in irradiance due to cloud cover.

Figure 3 below illustrates field data from a PV plant operating at around 90 MW power. The curtailment limit is initially changed from 100 MW to 82.5MW. The plant controller turns down the inverters (and turns off some of them if required) to achieve the new set point. Note that the turndown of power is gradual to meet the specified ramp-rate limit.

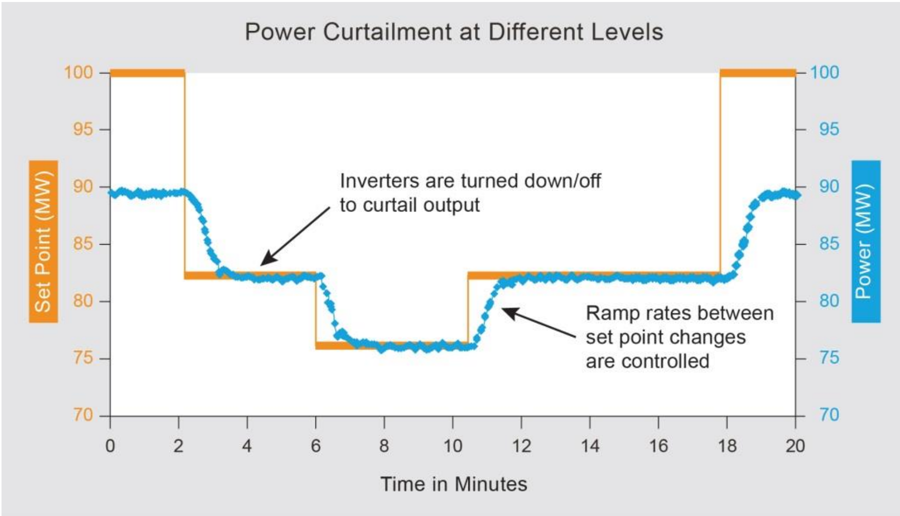

Figure 3 Power Curtailment at different levels

The curtailment limit is reduced again to around 75MW, and the controller responds as expected. When the limit is raised, the controller adjusts the output of the inverters to increase the total plant output. Finally, when the limit is raised to 100MW, the plant is no longer curtailed since the plant is producing less than the limit.

In all the control actions, the controller's command to each inverter is unique, given the specific conditions each inverter is experiencing. For example, when the plant is under curtailment, the plant controller can release the power limit of individual inverters if the total output of the plant starts falling below the set point. So in case of a cloud passage, which results in reduction of the output of a part of the plant, the controller can make the adjustment to increase output of other inverters that are not impacted.

The plant-level control strategy results in capture of energy from inverters that would have been otherwise unnecessarily curtailed. This concept is illustrated in Figure 4 below. The left side of the figure represents the reduction in power output of some of the inverters (grouped in blocks for illustration purpose) due to partial cloud cover. The controller commands other inverters that are not impacted by the cloud cover to dynamically increase their previously curtailed limit. Since the total potential power of the plant is greater than the specified plant output limit (illustrated on the right hand side of Figure 5), the plant is able to output the total power all the way to the limit.

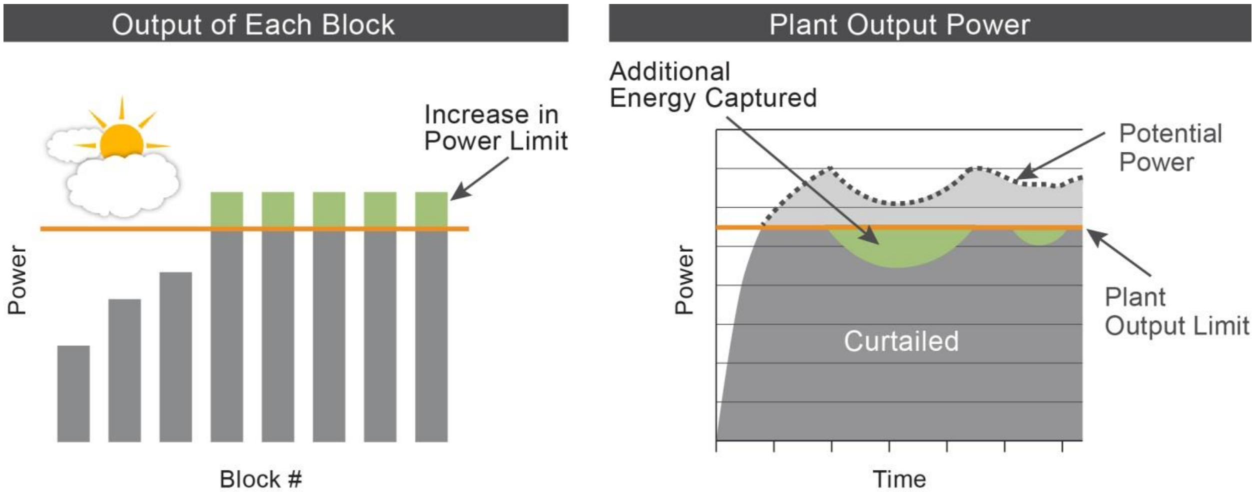

Figure 4 Impact of Cloud Passage under Curtailment

The plant control system can be set to operate in one of the three modes of automatic voltage regulation (AVR): voltage-regulation, power-factor regulation or reactive-power control.

In the voltage-regulation mode, the controller maintains the specified voltage set point at the POI by regulating the reactive power that is produced by the inverters as well as other devices such as capacitor banks. In the power-factor regulation mode, the controller maintains the specified power factor. The operation of the controller is illustrated in Figure 5 below, which shows field data from a PV plant producing about 212MW of active power at that time.

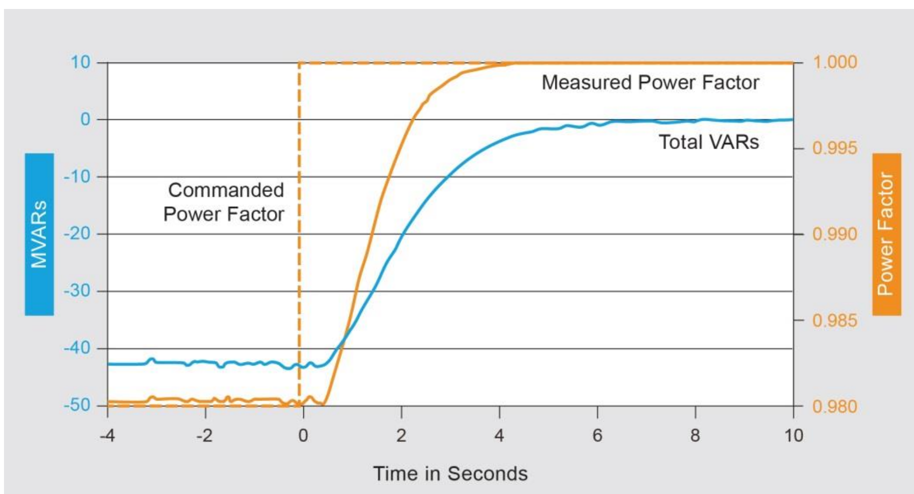

Figure 5 Dynamic Power-Factor Regulation

The figure illustrates the response of the plant when the power factor set point is changed from 0.98 to 1.0. The controller commands hundreds of inverters in the plant to change their reactive power output to meet the new power factor set point, using a closed-loop control mechanism. The figure illustrates that the inverters respond very rapidly. Within a few seconds (< 4 s) the new set point is achieved in a closed-loop control mode. More specifically, the rise time to reach 90% of steady-state value shown above is about 3.2s.

Frequency Droop Control

Using the active power management described previously, the control system also provides frequency droop control to handle unusual grid situations. For example, in case of above normal frequency, the controller will reduce the active power of the plant. If the plant is under curtailment, the power can also be increased if the below-normal frequency is detected.

Fault Ride-Through Capability

A significant benefit of utility-scale PV systems that incorporate fault ride-through capability is that they do not trip off during system disturbances, but continue to provide power when the grid needs it. The ability to ride through specific low and high voltages or low- and high-frequency ranges is being designed effectively into all modern variable generators. Most utility-scale inverters have this capability. With proper design practices, the PV plant is engineered to ensure that all components besides inverters also have the ability to ride-through short-term grid events.

Plant Modeling and Validation

The purpose of model validation is to ensure the proper performance of the control systems and validate the computer models used for stability analysis. To some extent, models used in system studies are intended to facilitate the use of field test data as a means of obtaining model parameters. The models are, however, reduced order and do not necessarily represent all of the control loops in the system. A model for the utility-scale PV plant with the plant controller described earlier was developed using recommendations of Western Electricity Coordinating Council (WECC-REMTF, 2012). The plant equivalent model is configured as shown in Figure 6, where multiple medium voltage feeders are equivalenced (Muljadi, et al., 2006) at one collector 34.5 kV bus at low side of the plant substation transformer. The dynamics related to the DC side of the inverter (PV array dynamics, inverter DC link and voltage regulator) are ignored for simplification (see (Morjaria, et al., 2014) for details of the model).

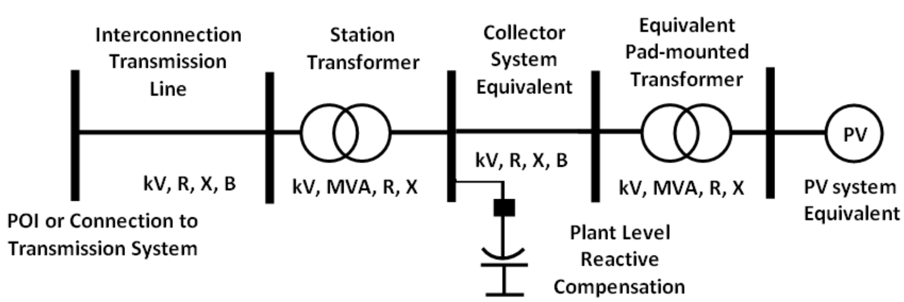

Figure 6 Single-machine equivalent load flow representation

The model was field tested using performance from a PV plant when operating at 90 MW active power output. Load-flow model equivalencing is performed using method as suggested in WECC modeling guide for solar PV plants (M&VWG/TSS, 2011). This plant uses SMA 800kVA inverters controlled by First Solar's power plant controller. The power plant controller allows coordination of all on-line inverters for plant-level voltage regulation at the POI, located at the 500 kV substation bus. Data captured from the field tests were filtered and then compared to simulation results obtained from plant model built in GE's PSLF simulation software. A 12 MVAR capacitor bank switching test is performed to examine the model performance (see Figure 7).

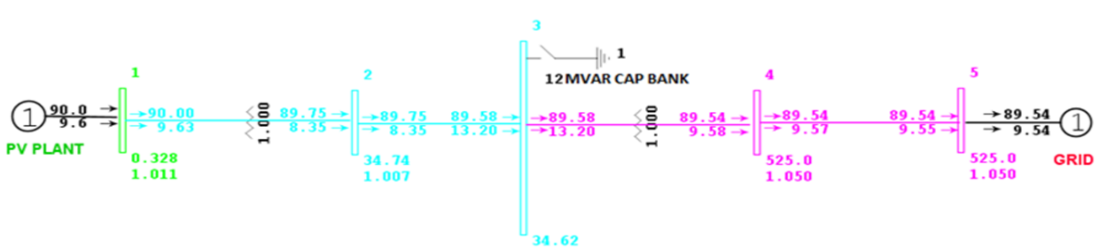

Figure 7 PSLF Equivalent Model for plant under test

In simulation model, a 12 MVAR capacitor bank, located at the 34.5kV collector bus, is engaged as an external stimulus. Figure 8 illustrates that, when the capacitor bank is engaged at "t = 0" seconds relative time, power plant controller sends control signals to each individual inverter to address immediately this switching event and eventually inverters reactive power contribution to the plant drops. The plant controller reactive power command (Qcmd_actual) distributed to the individual inverters is shown in green in Figure 8. Both, field measured reactive power command (Qcmd_actual) and simulated model command (Qcmd_simulation) are also shown in the figure. It illustrates initial quick response by PV plant, which took almost 100ms, followed by dominance of power plant controller in the order of seconds, to maintain post-disturbance stability.

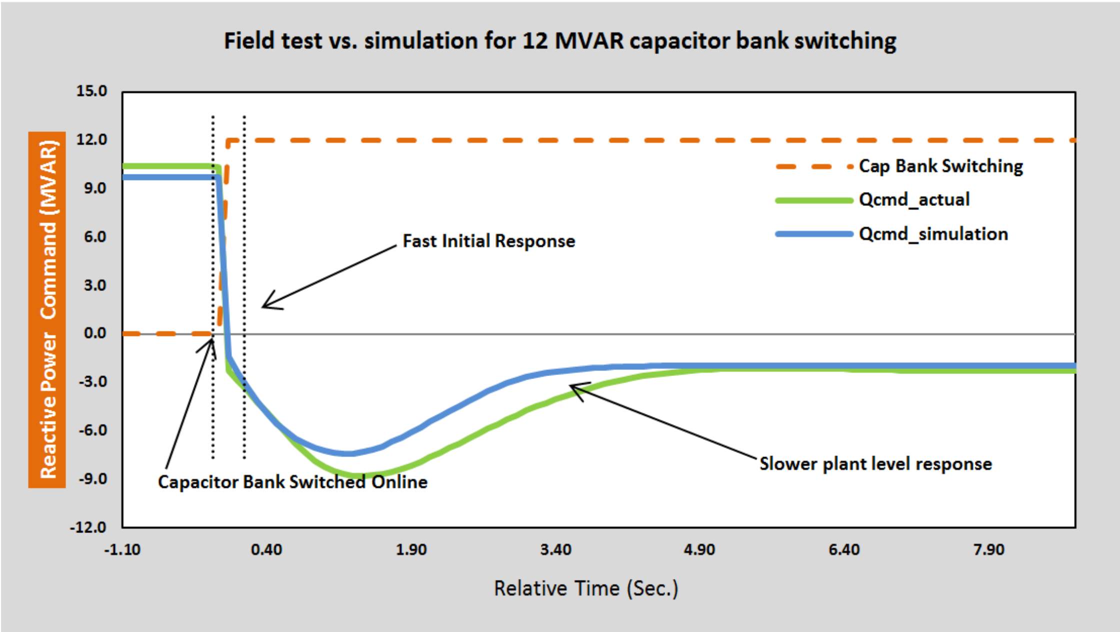

Figure 8 Qcmd response Field Test vs. Simulation

Figure 9 shows the detailed plant reactive power response to capacitor switching. This figure illustrates that the simulation model adequately mimics actual plant behavior. The response matches closely, with a difference immediately following the switching operation which could be attributed to the lower sampling rate in the field measurement compared to PSLF simulation.

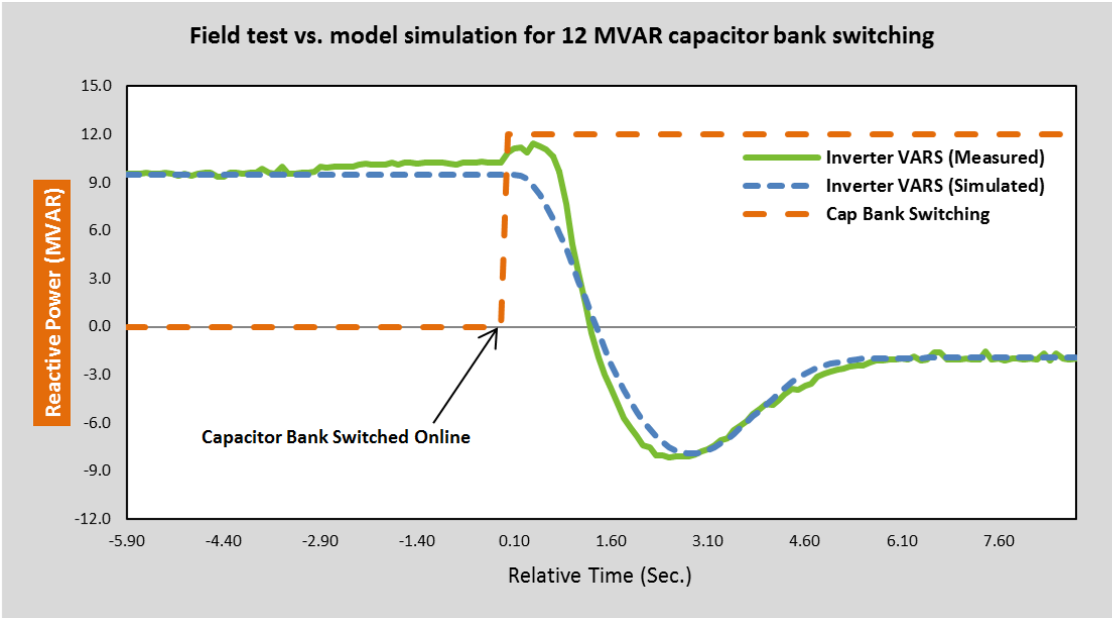

Figure 9 Inverter VARs during 12 MVAR Cap bank switching test

Plant Operation Under Abnormal Conditions

The grid-friendly features for utility-scale PV generation are generally not widely known. The grid operators typically require the utility-scale PV plants to operate them at constant power factor, often at unity power factor. This is also the case for the utility-scale Agua Caliente PV plant developed by First Solar. The plant which is located in Arizona near the California border as illustrated in Figure 10. The plant interconnects to a 500kV transmission line that has several other generation plants on the line including the Palo Verde Nuclear Generating Station which is located near Tonopah in western Arizona. It is the largest power plant in the United States generating about 3.3 GW.

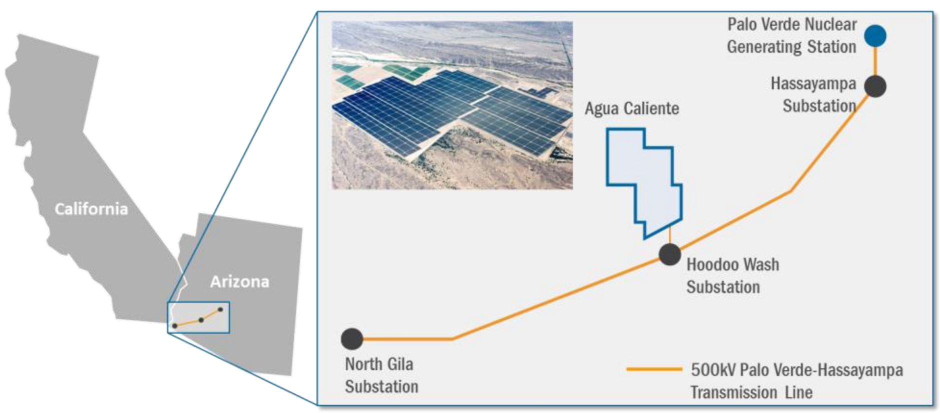

Figure 10 Agua Caliente Utility-scale PV Plant

Figure 11 shows a typical normal daily operation of this 290MW plant. Note that the nominal transmission line voltage (540kV) is maintained pretty tightly given the presence of large generators on the transmission line. The PV plant maintains unity power factor at the POI during its daily operation while the active power follows the typical PV generation profile. Note that during the middle of the day, the plant is capable of producing more power but is restricted to 290MW due to the interconnection and power porches agreement limit of the plant.

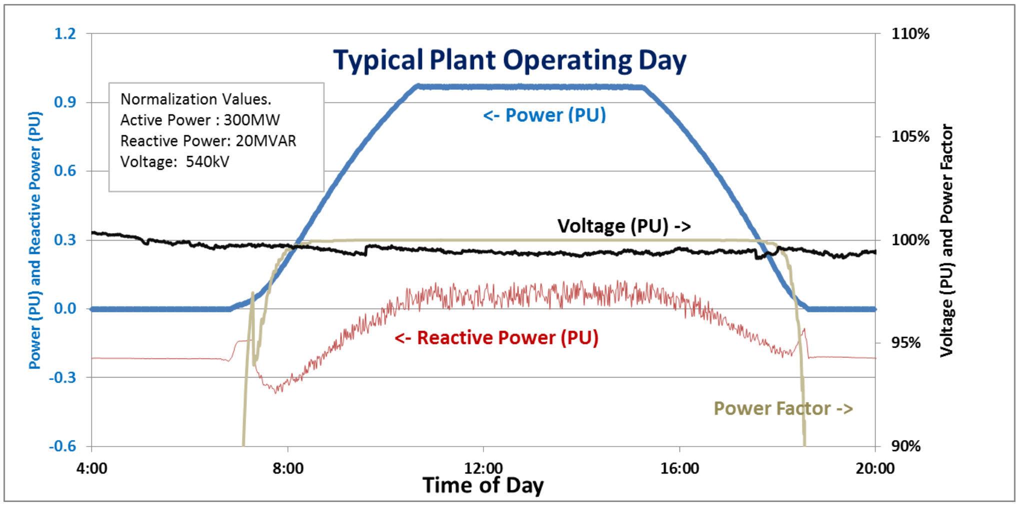

Figure 11 Normal Daily Operation of 290 MW PV Plant

On March 21, 2014, an interesting contingency took place when the transmission line between the Palo Verde generating station and the Hassayampa substation (see Figure 10) was taken out of service. This caused the line voltage on transmission line to start deviating. Recognizing that the Agua Caliente plant was equipped with various “grid-friendly” features, the grid operator requested the plant to support maintenance of the line voltage. As can be seen in Figure 12, by changing the mode of PV plant operation the line voltage was stabilized. At the end of the day, when the PV plant went off-line the line voltage started fluctuating again.

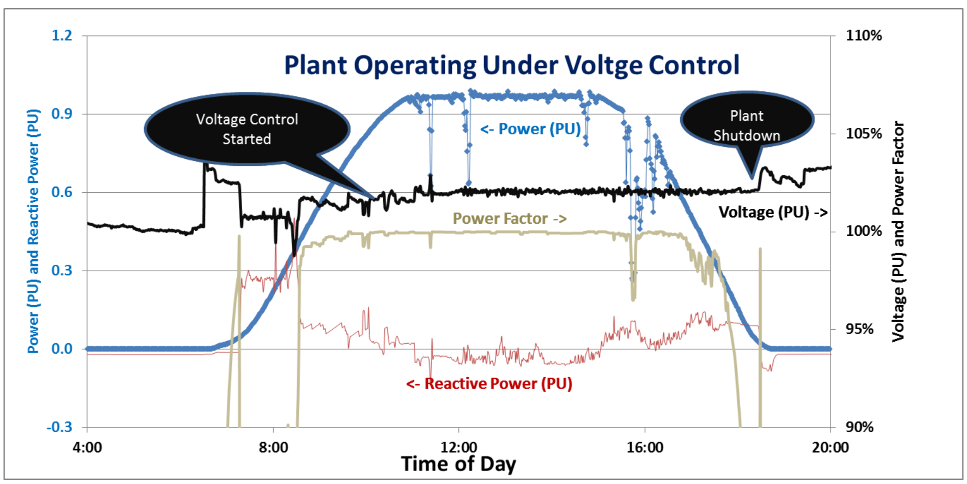

Figure 12 Agua Caliente Plant on March 21, 2014

This event provides some key lessons. One, the ability to operate the PV plant in various modes is critical to overall grid stability and reliability. Two, even though the various features described in this paper may not be mandated, it is important to recognize that with increasing penetration, the PV plants will be called upon to support the grid. Having these features already available make the plants valuable. We are now routinely incorporating these features in various utility-scale PV plants.

Summary

We have described a utility-scale grid friendly PV power plant that incorporates advanced capabilities essential to supporting grid stability and reliability. It includes features such as voltage regulation, active power controls, ramp-rate controls, fault ride through, and frequency control. These capabilities provide the intrinsic benefits of reliable plant operation in the grid, which in turn results in additional plant yield and potential additional revenue. Such capabilities are essential for the successful deployment of large-scale PV plants. A critical component is a plant-level controller that is specifically engineered to regulate real and reactive power output of the solar facility such that it behaves as a single large conventional generator. Accurate plant model that supports power systems planning is also necessary for successful deployment. We conclude with a description of an event where the PV plant was able to support the grid during an abnormal condition.

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