A RECENT RAPID PHOTOVOLTAIC (PV) price reduction has significantly increased the competitiveness of PV-generated electricity, which has now reached grid parity in many markets, i.e., electricity is produced at the same or a lower price than conventional electricity sources. Along with other factors stimulating the global growth of renewable energy, this cost decline has greatly increased both the number and size of utility-scale solar plants, especially PVs, that are deployed on the power grid. The impact on power systems of integrating PV generation, especially as it relates to grid reliability and stability, needs to be addressed.

A typical 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. Through sophisticated control functions, however, the PV plant is able to contribute actively to grid stability and reliability and operate effectively in the grid.
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 to provide their share of grid support. 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.

In this article, we describe our design of a grid-friendly PV plant, including the development of a plant controller that complies with these requirements, resulting in a PV plant that actively contributes to the reliability and stability of electrical transmission and distribution system. Field data from First Solar-developed utility-scale PV plants are used to illustrate the concepts. The grid-friendly PV plant also includes the ability to ride through specific low and high voltages or low- and high-frequency ranges.

We have described a utility-scale, grid-friendly PV power plant that incorporates advanced capabilities essential to supporting grid stability and reliability.
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Power Plant Controller Architecture
A key component of a grid-friendly PV power plant is a plant-level controller. It is designed to regulate real and reactive power output from the PV plant, such that it behaves as a single large generator. While the plant is composed of individual small generators (or, more specifically, inverters), with each generator 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 active power control and voltage regulation (through reactive power regulation).

The plant controller 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.

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 a rapid response to commands from the plant controller. Typically there is one controller per plant controlling the output at a single high-voltage bus (referred to as POI). The commands to the plant controller can be provided through the supervisory control and data acquisition system (SCADA) human-machine interface (HMI) or even through other interface equipment, such as a substation remote terminal unit.

Figure 1 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.

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, the 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 plant controller dynamically stops and starts inverters as needed to manage the specified active power curtailment.

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Dynamic Voltage Regulation Modes

Through the SCADA HMI, 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. The three AVR modes are illustrated in the SCADA HMI screen shown in Figure 2. Note that the plant can operate in only one of the three operating modes at any time.

In the voltage-regulation mode, the controller maintains the specified voltage set point at the POI by regulating the reactive power 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 3, which shows field data from a PV plant producing about 212 MW of active power at that time.

Figure 3 illustrates the response of the plant when the power factor set point is changed from 0.98 to 1.0. The controller commands the inverters 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 in the figure is about 3.2 s.

Active Power Curtailment

Current SP  New SP
Active Power Limit  290.00  [290.00] MW
Ramp Up Rate  15.0  [15.0] MW/min
Ramp Down Rate  15.0  [15.0] MW/min

Active Power Management

Through the SCADA HMI, the controller can also be set to control the active power output of the plant. 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. Note that, in some cases the plant controller will turn off certain inverters to achieve this desired set point since the output of each inverter cannot be lowered below a certain threshold without causing a high dc voltage operating condition.

Figure 4 illustrates field data from a PV plant operating at around 90-MW power. The curtailment limit is initially changed from 100 to 82.5 MW. 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.

The curtailment limit is reduced again to around 75 MW, 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 100 MW, 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 a reduction of the output of a part of the plant, the controller can make the adjustment to increase the output of other inverters that are not impacted.

The plant-level control strategy results in a capture of energy from inverters that would have been otherwise unnecessarily curtailed. This concept is illustrated in Figure 5. The left side of the figure represents the reduction in power output of some of the inverters (grouped in blocks for illustration purposes) 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 (as 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 7. Plant shut-down and start-up controls.

Figure 8. The frequency droop function.
The grid-friendly PV plant also includes the ability to ride through specific low and high voltages or low- and high-frequency ranges.

An illustration of an additional function related to active power management is shown in Figure 6, which shows the reaction of the plant when it is shut down and started up. The field data in this case illustrates when one block (30 MW), which is under the control of the plant controller, is commanded to shut down. The active power management function reduces plant output while maintaining the required ramp rate. As mentioned earlier, some inverters are turned down while others are shut down. Note that the control is quite effective even with moderately varying irradiance conditions.

Figure 7 also illustrates the plant start command resulting in the controller gradually increasing the plant output by adjusting the inverters’ output and turning on the inverters in sequence.

**Figure 9.** An overall model structure of a solar PV plant.

**Figure 10.** An REPC_A model block diagram.
Frequency Droop Control
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, as illustrated in Figure 8. If the plant is under curtailment, the power can also be increased if the below-normal frequency is detected. Note that all the parameters illustrated in the figure are configurable and are shown here for illustrative purposes only.

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 in addition to inverters also have the ability to ride through short-term grid events.

Modeling and Validation
A general structure of a PV power plant recommended by the Western Electricity Coordinating Council (WECC) is shown in Figure 9. For the simplification of a solar PV plant, the dynamics related to the dc side of the inverter (PV array dynamics, inverter dc link, and voltage regulator) are ignored. The overall model structure shown in Figure 9 represents the complete PV plant and consists of an equivalent generator model “REGC_A” to provide current injections into the network solution, an electrical control model “REEC_B” for local active and reactive power control, and a centralized plant controller model “REPC_A” to allow for plant-level active and reactive power control.

Power Plant Controller Model
The plant controller model REPC_A is used when plant-level control of active and/or reactive power is desired. A functional block diagram for REPC_A model is shown in Figure 10. The model incorporates the following functionalities Renewable Energy Modeling Task Force (WECC-REMTF):

- Closed-loop voltage regulation at a user-designated bus with the provisions for line drop compensation, voltage droop response, and a user-settable dead-band on the voltage error signal.
- Closed-loop reactive power regulation on a user-designated branch with a user-settable dead-band on the reactive power error signal.
- A plant-level governor response signal derived from frequency deviation from the nominal user-designated branch. The frequency droop response can be applied to active power flow on a user-designated branch. Frequency droop control is capable of being activated in both over and under frequency conditions. The frequency deviation applied to the droop gain can be subject to a user-settable dead-band.

Test Model Description
This section demonstrates the outcome from a set of field tests performed at a PV plant when operating at 90-MW active power output. The test plant equivalent model is configured as shown in Figure 11, where multiple medium-voltage...
feeders are equivalenced at one collector, a 34.5-kv bus at the low side of the plant substation transformer. Load-flow model equivalencing is performed using the method suggested in the WECC modeling guide for solar PV plants Modeling and Validation Work Group/Technical Studies Subcommittee.

This plant uses SMA 800-kVA inverters controlled by First Solar’s power plant controller. The power plant controller allows for coordination of all online inverters for plant-level voltage regulation at the POI, located at the 500-kV substation bus. The purpose of testing at this plant is for the model validation of First Solar’s controller against WECC’s proposed power plant controller. Data captured from the field tests were filtered and then compared to simulation results obtained from a plant model built in GE’s Positive Sequence Load Flow (PSLF) simulation software. A single-line diagram of the plant model in PSLF is shown in Figure 12. A 12-Mvar capacitor bank switching test is performed to examine the plant controller performance.

In the test system, a 12-Mvar capacitor bank, located at the 34.5-kv collector bus, is engaged as an external stimulus. Figure 13 illustrates that, when the capacitor bank is engaged at “t = 0” s relative time, the power plant controller sends control signals to each individual inverter to immediately address this switching event, and eventually inverters reactive power contribution to the plant drops. First Solar’s power plant controller reactive power command (Qcmd_actual) distributed to the individual inverters is shown in green in Figure 13. Both field measured reactive power command (Qcmd_actual) and simulated model command (Qcmd_simulation) are shown in Figure 13. The figure illustrates the initial quick response by the PV plant, which took almost 100 ms, followed by the dominance of the power plant controller in the order of seconds, to maintain post-disturbance stability.

Figure 14 shows the detailed plant-reactive power response to capacitor switching. This figure illustrates that the simulation model performance adequately mimics actual plant behavior. The response closely matches actual behavior, with a difference immediately following the switching operation that could be attributed to the lower sampling rate in the field measurement than in PSLF simulation.

### Daily Grid Operation

Another grid integration concern, especially for a grid operator, is daily 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
In all the control actions, the controller’s command to each inverter is unique, given the specific conditions each inverter is experiencing.

short-term solar generation forecasts is facilitating continued efficient and reliable system operations. By providing PV plants that can support the forecasting needs of grid operators, this variable resource can address the load-balancing needs of grid operators. An advantage of solar in many markets is that its peak generation coincides with higher load demand, making it more a valuable generation resource.

**Grid Flexibility and Power Systems Resource Planning**
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 an increased use of conventional resources that are able to respond and ramp up more quickly and a reduced use of inflexible generation resources. A recent analysis points 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.”

**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 successful the deployment of large-scale PV plants.

A key component of such a grid-friendly plant is a plant-level controller specifically engineered to regulate real and reactive power output of the solar facility such that it behaves as a single large conventional generator, although within the limits dictated by the intermittent nature of the solar resource. In cases where the plant output is constrained but the plant has additional generation capability, this controller can reduce the impact of cloud passage and increase overall yield. Plant-model validation against measured field data demonstrates that the WECC-proposed model for a solar PV plant is adequately capturing actual plant behavior.

**For Further Reading**

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