Reactive Compensation and Voltage Control with PV Generation Resources

Support Grid Stability with Unified Control and Pinpoint Precision

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Business Value

- Support grid stability
- Meet proposed regulatory requirements with existing control systems and devices
- Deliver precise VARs to manage voltage at the point of interconnection
- Unify management of PV resources including inverters and capacitor banks

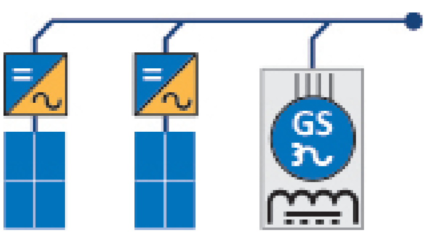
One of the greatest challenges faced by utilities today is to ensure that variable generation resources, such as solar, contribute to the reliable operation of the electric grid. The high penetration of these variable generation resources has changed the power grid landscape requiring new sources of reactive power and the need for voltage control. These variable generation resources are replacing synchronous generators which traditionally supplied the voltage regulation to the utility grid. In California, the California Independent System Operator (CAISO) and California Public Utilities Commission (CPUC) Rule 21 Smart Inverter Working Group (SIWG) are developing proposals and regulations to require that all asynchronous resources provide reactive power capability and voltage control utilizing the capabilities of the PV inverters.

To meet the total reactive power requirements beyond the reactive capability of the inverters, the solar generation facility may need to install additional dynamic or static reactive power devices. These dynamic and static devices must be managed and controlled in coordination with PV inverters to effectively maintain the voltage at the Point of Interconnection (POI).

Unified Control of Voltage and Reactive Power

This paper discusses the capability of solar generation facilities and their role in providing voltage control and reactive power by coordinating functions of PV inverters and dynamic/static reactive devices. This paper also identifies design considerations that enable coordination and control of both the dynamic and static reactive devices to maintain desired voltage at the POI.

I. Introduction



The growing penetration level of non-traditional renewable generation resources such as solar has led to the need for renewable resources to contribute more significantly to the power grid's voltage and reactive power regulation. Solar installations in the United States are expected to reach 7.9 GW in 2015 with an additional 16 GW by the end of 2016.[1]

All electric power transported or consumed in distribution and transmission networks consists of both real power and reactive power. Real power (Watts) accomplishes the useful work to serve electric loads while reactive power (VARs) is essential to move real power through transmission and distribution lines to the customers. Both real power and reactive power are fundamental, inseparable, and necessary to the effective operation of the electric power system.

Traditionally, synchronous generators have supplied the reactive power capability to the grid. With the growth of solar generation resources, synchronous generators are being replaced by solar facilities. The real power component from synchronous generators have been replaced with solar generation but the need to replace the reactive power component from synchronous generators has been ignored. This loss of reactive power has become a burden to the remaining resources connected to the grid. Without adequate supply of reactive power, the electrical system cannot reliably deliver real power to the customer; and thus new sources of reactive power must be found to support the grid.

For proper operation of electrical equipment connected to the grid, voltage control in an electrical power system is important to prevent damage from overheating of generators and motors, reduce transmission and distribution losses, and withstand and prevent voltage collapse that can result in widespread system outages. Voltage collapse occurs when the electric system tries to serve more load than the voltage can support. Voltage control can be properly maintained by the generation or consumption of reactive power. Generation of reactive power will increase the system voltage while consumption of reactive power will decrease the system voltage.

Without adequate supply of reactive power, the electrical system cannot reliably deliver real power.

Voltage control in distribution systems is typically performed at the distribution substation level. Voltage regulation by distributed energy resources (DERs) such as solar, originally was not permitted by the IEEE 1547 standard. These intermittent generation resources typically operated at unity power factor with respect to the local system. In 2014, IEEE 1547a was adopted and voltage regulation by solar generation resources is now permitted.

II. PV Facilities Dynamic Reactive Capabilities

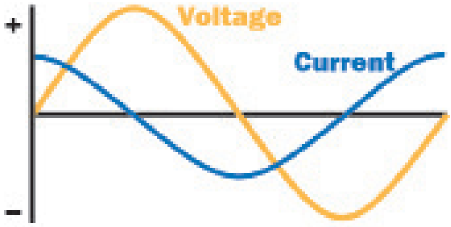
Solar generating facilities use PV inverters (power converters) to convert the variable DC power from the solar panels into 60 Hz AC power. These PV inverters also have reactive power capability integrated into the inverter's advanced control features. The inverters have the capability to consume or generate reactive power provided that their current and terminal voltage ratings are not exceeded. The reactive capability of these inverters is limited by their internal current, voltage, and temperature constraints; therefore, PV inverters can continue to provide reactive capability at partial power output.

Reactive power compensation is the most effective way to improve both power transfer capability and voltage stability in an electric system. The control of voltage levels is accomplished by managing the generation or consumption of reactive power in the electric system. Since PV inverters have reactive power capability, they can provide immediate reactive power support to the grid for voltage regulation.

Reactive power requirements for interconnection agreements are specified at the POI (Point of Interconnection). Typical interconnection requirements for reactive capability of synchronous generators specify 0.95 power factor lag to lead at the POI. This requirement means that the generating facility must be capable of generating (lagging power factor) or consuming (leading power factor) approximately 1/3 of its real power (MW) rating in total reactive power (MVAR).

Depending on the interconnection agreement and PV inverter, a solar generating facility can rely on the inverters to provide a portion or all of the necessary reactive power requirements at the POI. Furthermore, the total reactive power capability of a solar plant can be supplemented with additional dynamic and static devices such as STATCOM, SVC (static VAR compensator) or switched shunt capacitors and reactors to meet the reactive interconnection requirements.

III. Static and Dynamic Reactive Devices



Fixed shunt capacitors and reactors can be used to shift the dynamic reactive capability of a generating facility to a lagging or leading power factor respectively. These static reactive devices can be used to supplement the total reactive capability of a generating facility. If there is insufficient dynamic reactive power availability from other devices at the facility, SVCs or STATCOMs can be used to increase the total dynamic reactive power capability of the facility.

Shunt capacitors provide static passive compensation. They are either permanently connected to the power system or switched. These devices are normally installed at substations for producing reactive power while allowing nearby generators to operate near unity power factor. Shunt capacitors are relatively inexpensive but have their shortcomings. An operational disadvantage of using a capacitor bank is that the reactive power output is proportional to the square of the voltage. As voltages fall, the capacitor's reactive capacity output will decrease which may contribute to further voltage degradation.

SVC (Static VAR compensators) devices provide active compensation and have fast switching capability. The device can generate or absorb reactive power in sub cycle time frames. SVCs can provide rapid control of temporary over voltages but they have limited overload capability. Because SVCs use capacitors, they suffer from the same degradation in reactive capability as voltage drops. Once an SVC reaches its reactive generation limit, voltage instability may occur since the critical or collapse voltage will become the SVC regulated voltage.

The STATCOM (Static compensator) is a solid-state shunt device that provides active compensation and generates or absorbs reactive power. The device uses power electronics to synthesize the reactive power output. The STATCOM offers symmetrical generating and consuming reactive power capabilities. The solid-state nature of the STATCOM enables fast and effective voltage control. STATCOMs are current limited so the reactive capability responds linearly to voltage in comparison to the voltage squared relationship of SVCs and capacitors. This attribute increases the effectiveness of STATCOMs to prevent voltage collapse. Unfortunately, STATCOMs can be quite expensive and may not be cost effective for all generating facilities.

IV. Reactive Compensation and Voltage Control Considerations

Power Plant Controller:

The reactive capabilities of PV inverters are measured at the inverter terminals. Interconnection reactive requirements are specified at the POI. Between the POI and the inverter terminals are a network of conductors that deliver the real power from each inverter to the POI. Reactive power cannot be transported over long distances without reactive losses and these losses will contribute to the load demand. These additional reactive load requirements must be compensated when calculating the reactive power that needs to delivered to the POI from the inverters. To mitigate this issue, an integrated SCADA solution such as the Trimark T1-S Gateway or a power plant controller (PPC) can be implemented. These devices provide closed loop control to obtain an optimum voltage profile and reactive power flow at the POI.

Since the point of control for generating facilities is designated at the POI, an accurate and reliable power meter is necessary and critical to measure the electrical parameters at this location. This power meter must be connected to the PPC network. Measurements such as real power, power factor, reactive power, voltage, and frequency will provide feedback to the PPC. These "Real-time" feedback values will allow the PPC to coordinate its operations with the inverters and reactive devices resulting in the necessary voltage changes at the POI.

Static and Dynamic Reactive Device Applications:

Sufficient static and dynamic voltage support is needed to maintain the voltage at the POI. The type of reactive compensation for the voltage support should be based on time recovery expectations and operational requirements. Static reactive devices should not be used for reactive support where requirements are needed at sub-cycle response time. Rather they should be used to supply the normal reactive load requirements. Dynamic reactive devices should be used for instantaneous responses to system transients or events. Proper balance of static and dynamic devices is necessary to maintain the system voltage.

The PPC should be developed to evaluate the real time POI conditions and determine which reactive device is most effective to meet the desired result at the POI. Ideally, the static devices should be used to supply the normal reactive loads for the generating facility. As load increases or transients occur, the dynamic reactive capabilities from PV inverters can be used to generate or consume reactive power to maintain the system voltage.

Reactive Device Capabilities and Limitations:

The reactive capacity and control capabilities and limitations of each reactive device must be understood prior to developing a PPC closed-loop control to provide reactive support and voltage control at the POI. For example, some shunt capacitors must be properly discharged (typically with a duration of 5 min) after being disconnected from service before they can be placed back into service.

It is essential to coordinate switching of static reactive devices and inverters while developing closed loop control logic.

Switching of static reactive devices should only occur as necessary. Static reactive devices should only be switched to add reactive power beyond the inverters' maximum capacitive capability. Proper switching of the shunt capacitors should be managed to extend the dynamic range of a generating facility. Excessive and unnecessary switching of capacitor banks may cause thermal, mechanical, and dielectric stress of electrical equipment downstream; therefore, it is important to coordinate the switching of static reactive devices and inverters while developing the PPC closed loop control.

Power Factor and Reactive Power Modes:

Solar generating facilities are typically designed to operate within a voltage schedule. This voltage schedule allows the facility to operate within its reactive capability range during normal operating conditions. The utility may also expect the site to operate at unity power factor at the POI within a defined nominal operating voltage range. Outside of this nominal operating voltage, the utility may require voltage regulation.

When the system voltage is operating outside of the nominal conditions, the facility is expected to operate at the capacitive high end of its reactive range during low voltage situations or events and the inductive high end of its reactive range under light load conditions.

Since most inverters have both power factor and reactive power capabilities, selection of the correct reactive mode is critical to meeting the utility's reactive compensation and voltage requirements. The PPC logic should have the intelligence to determine when the facility must provide unity power factor control (providing the exact amount of reactive power needed to equal what is consumed) and voltage control (maintaining voltage levels at exactly the correct operating levels at the POI regardless of how much reactive power is required).

Voltage Deviation Smoothing:

Most PV inverters have a power factor capability of 0.90 lagging/ 0.90 leading at nominal output and operating voltage. The total dynamic reactive capability of the site can be calculated from the inverters at nominal output. Once the total reactive capability of a site is determined, it is important to know what percentage of the site's reactive capability is dynamic and static. The dynamic reactive power reserves should be maintained and used quickly to respond quickly to changing reactive power demands and maintaining voltages through the electrical system. When static reactive devices are switched in by the PPC, all reactive devices in service must be coordinated and controlled by the PPC with an appropriate dynamic reactive power ramp rate to smooth any voltage deviations due to switching activity or discrete reactive control steps.

Reactive Power from Inverters at Low Irradiance:

During periods of low irradiance, the DC voltage for the solar inverters may limit the reactive capability of the inverters. A minimum output level should be defined for these conditions and a reduced power factor range or a permissive reactive power range should be considered and applied at the POI from the PPC.

Plant Control Coordination:

Finally, the PPC must be able to support a number of supervisory and control functions for the generating facility. The PPC processes measurements at the POI and commands issued from a remote operations center, utility, or system operator. The PPC control logic must be developed to allow the generating facility to operate in parallel with autonomous inverter controls and external control commands that

Figure 1: Reactive Capability Corresponding to 0.95 Lead to Lag at POI As a Function of POI Voltage

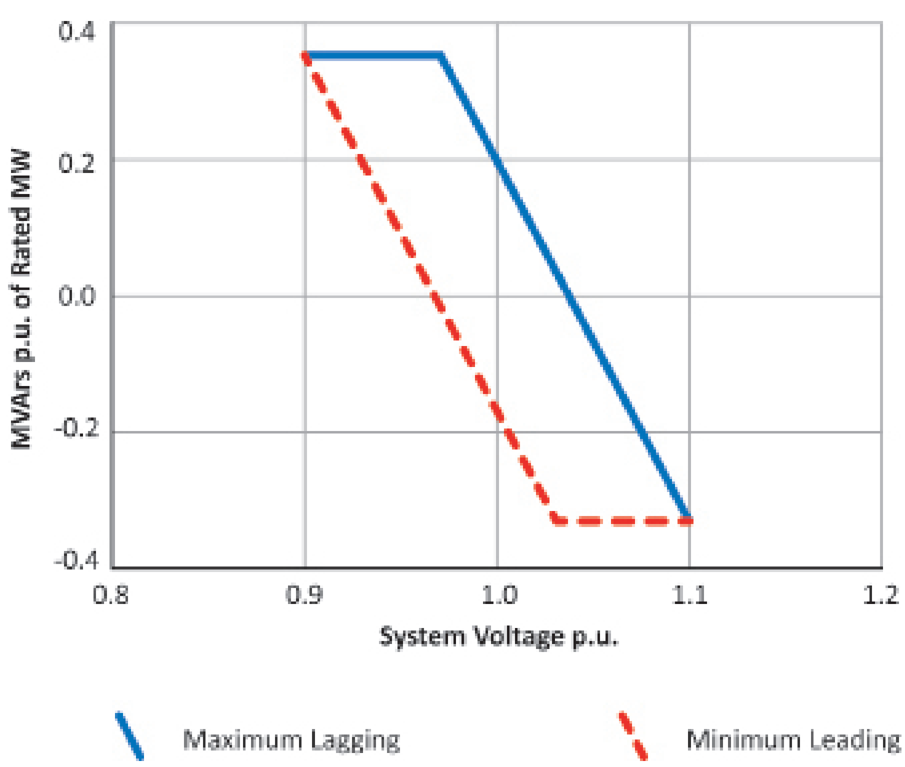
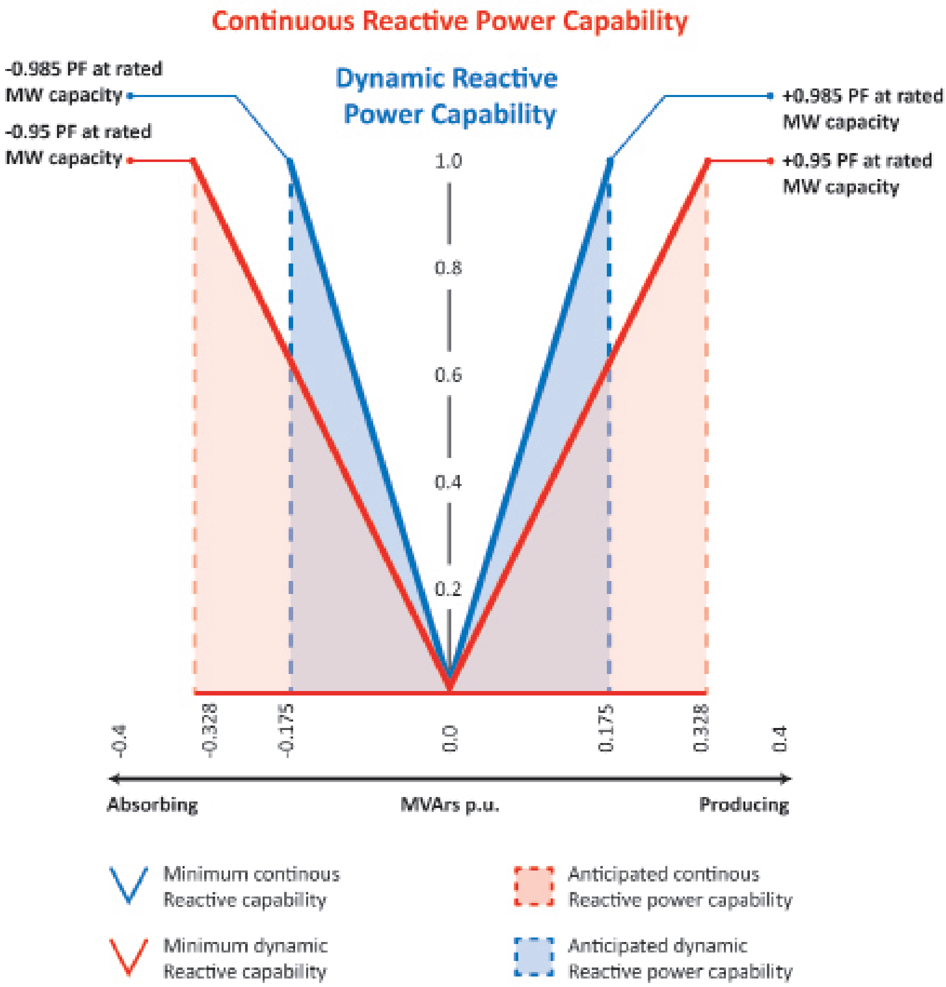


Figure 2: Dynamic Voltage Response at the POI



can be actively distributed over a portfolio of generating facilities. Proper management and control of the reactive devices by a PPC is critical to reactive compensation and voltage control. Improper coordination of these devices may lead to increased reactive power losses, reduction in reactive reserves necessary for transient events or light loading conditions, excessive switching of reactive devices that can lead to premature failure, or an increased probability of voltage collapse.

V. Reactive Power Standards

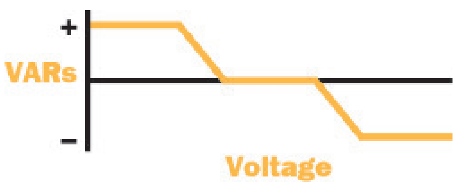
Regulatory and operational requirements between both utilities and PV site operators have created a need for the generating facilities to participate in grid support activities. Reactive power standards do currently exist in numerous jurisdictions that require uniform reactive power requirements. Jurisdictions such as the Electric Reliability Council of Texas (ERCOT), California Independent System Operator (CAISO) and Independent Energy System Operator (IESO) in Ontario, Canada have all implemented uniform reactive power requirements for asynchronous generators to compensate for unstable voltage conditions on the grid.[2] These jurisdictions believe that uniform reactive requirements will allow new renewable resources to connect to the grid without having to wait for new reactive resources to be interconnected.

The CPUC also issued a decision to adopt modifications to Electric Tariff Rule 21 to capture the technological advances of advanced inverter controls found in today's inverters. The CPUC and the California Energy Commission (CEC) created the Smart Inverter Working Group (SIWG) to discuss the technical capabilities of DER systems, develop the default DER functionality requirements including reactive power support, establish an implementation plan for California, and update California's Rule 21 DER interconnection requirements.[3]

Recently, the CAISO issued a Straw Proposal to adopt a uniform requirement for asynchronous resources to provide reactive power capability and voltage regulation. The CAISO believes that adopting a uniform reactive power and voltage control requirement for asynchronous resources will promote renewable integration and grid reliability. The CAISO's technical requirements for asynchronous resources include all generating facilities must be designed to have the capability of producing a net power factor of 0.95 lagging at the POI when voltage levels are between 0.90 and 1.00 per unit and absorbing a net power factor of 0.95

leading at the POI when voltage levels are between 1.00 and 1.10 per unit while the generating facility is at maximum real power output. See Fig 1. The asynchronous resource shall also provide dynamic voltage response between 0.985 leading and 0.985 lagging at rated power capacity at the POI using controllable dynamic and static reactive power support equipment. See Fig. 2

VI. Conclusion



The rapid growth of variable generation resources such as solar power has definitely created challenges to maintaining a safe and reliable grid. The traditional reliance of reactive support from synchronous generators is no longer an option and new reactive resources must be provided to support the high penetration of renewable resources to the grid. Reactive power and power factor control features from PV inverters are readily available and can be used for voltage regulation and reactive support. Using existing control technology from these inverters will promote renewable integration and grid stability. The addition of static and dynamic reactive devices can also supplement the total reactive support for a generating facility to maintain the system voltage. Utility-scale PV generation facilities must provide a SCADA solution such as the Trimark T1-S Gateway or PPC. These dynamic and static reactive devices must be coordinated and controlled to maximize a generating facility's maximum power output while maintaining the voltage requirements at the POI.

Coordination of reactive compensation and voltage control by PV facilities can extend the life of equipment, reduce maintenance costs, and defer costs for new reactive equipment

There are no technical barriers that would prevent inverters from actively controlling the voltage at the POI. Until regulatory requirements mandate reactive requirements from inverters, the inverter's full voltage support cannot be realized. These reactive support features are safe, reliable, and beneficial to the utilities as attested by Trimark's successful implementation of both inverter and capacitor bank controls at PV generating facilities. Reactive compensation and voltage control by PV facilities can extend the life of a utility's existing equipment, reduce the utility's maintenance costs, and possibly defer costs for new reactive equipment for future needs. It is time to transition PV generating resources from being a rival in reactive power support to a contributor to grid reliability. ■

VII. References

[1] B. Beetz, US: 16 GW of 32 GW Utility-Scale Solar Pipeline to be Completed by ITC Deadline, PV Magazine, 2015.

[2] C. Loutan, Reactive Power Requirements for Asynchronous Resources, 2015

[3] F. Cleveland, Recommendations for Advanced Functions for Distributed Energy Resources, 2015.

VIII. About the Author

Stephen Yee is Trimark's Director of SCADA Engineering and Security. He has 10+ years of experience in the solar generation industry. Prior to joining Trimark, Stephen was the Corporate Quality Engineering Director for SPI Solar where he was responsible for PV project engineering, design, testing, commissioning, and O&M. He also headed the startup of overseas manufacturing facilities including PV module and mechanical subassembly manufacturing.

Stephen has been instrumental in defining and developing the next generation of PV plant management and controls. He has applied power engineering concepts to real-world scenarios providing unprecedented control over PV inverters, trackers, capacitor banks and other IEDs to satisfy interconnection and regulatory requirements as well as provide dynamic grid support. He works directly with manufacturers of PV inverters, trackers, and PV resource equipment to develop and validate Trimark's control technology using laboratory test beds and simulation software before proving out control in production.

Case Study: Voltage Regulation

Background

This 20 MWAC photovoltaic (PV) generation resource is located in central California. The site generates power from 20 inverters.

Trimark's initial contract included:

- Installation and certification of CAISO-approved revenue meters, a Remote Intelligent Gateway (secure data telemetry), and meteorological instruments; and
- Plant SCADA. Trimark's T1-S Gateway monitors and controls PV inverters, trackers and related devices. Operators can access real-time monitoring and control of the plant and/or individual devices through Trimark's T1-S Vantage web-based HMI.

Issue

Based on a reactive compensation study and interconnection requirements, the site was required to provide Automatic Voltage Regulation (AVR) at the point of interconnection (POI) – a 70 kV substation located over a mile from the generation facility.

Solution

Upon PG&E's notification that AVR was required for the site, the resource owner contracted Trimark to design and develop an economically prudent AVR control solution.

Instead of installing new dynamic reactive devices to provide voltage regulation, Trimark developed and configured PLC functionality included in T1-S Gateway, the plant SCADA system. This solution leverages the PV inverters' reactive control modes to accomplish PG&E's AVR requirements. And it does it at a fraction of the cost that would be required to install new devices and infrastructure.

Trimark designed and developed the control scheme to maximize the site's energy generation while maintaining voltage and meeting reactive requirements at the POI. Trimark's plant controller polls real-time data from the revenue meter at the POI and uses that data to drive automated control decisions.

Technical Approach to Voltage Compensation Logic

The inverter's reactive control capabilities provide either capacitive or inductive reactive requirements outside of the nominal operating voltage limits. Within nominal operating voltage limits, the inverters are controlled to provide near-unity power factor at the POI. If the interconnection voltage schedule changes, the site voltage settings can be reconfigured by the site operator through T1-S Vantage.

For voltages below 0.90 pu (or where additional capacitive reactive power requirements beyond 0.90 lagging are necessary), the plant controller manages the site inverters to inject (boost) MVARs at the POI to increase the voltage.

For voltages above 1.10 pu (or where additional inductive reactive requirements beyond 0.90 leading are necessary), the plant controller manages site inverters to absorb (buck) MVARS at the POI to decrease the voltage. Voltage and VARs measurements from the CAISO meter, located at the POI, provide feedback to the T1-S plant controller which in turn automates real-time logical commands to achieve the desired state. Reactive power ramp steps and limits are applied to minimize voltage deviations while achieving PF and voltage requirements at the POI.

The AVR control scheme has been successfully tested and approved by PG&E. ■

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