Requirements for Analyzing T&D Operations for High-Penetration PV

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Introduction

The development of high-penetration photovoltaic (HPPV) modeling tools requires identification of the critical aspects of Transmission and Distribution (T&D) system operations and interaction with solar operations. The following report describes the basic requirements recommended for HPPV model integration with T&D Planning, along with scenarios to demonstrate the need and effectiveness of the models.

1. Requirements for HPPV Interconnection Modeling

The appropriate time frame for analysis should be identified for each type of study. Steady state capacity issues (minutes to hours), voltage regulation (seconds to minutes), and transient interactions (a second or less) all require identification of the specific time domain and scenario to study. Data requirements are different for each type of study. Additionally, interactions between the photovoltaic (PV) system and the electric system operations that are of concern to the utility planner need to be identified and addressed. IEEE 1547, “Standard for Interconnecting Distributed Resources with Electric Power Systems” provides an understanding of the issues with which utility planners and the Generation Interconnection (GI) requestor need to be familiar.

1.1 HPPV Modeling Scenarios

The modeling scenarios recommended for interconnection studies are discussed below.

1.1.1 Large Single PV Source (>1 MW)

A large PV array, consisting of hundreds or even thousands of PV panels and multiple inverters linked together to one or multiple points of common coupling (PCC) creating a net interconnected PV generating capacity of 1 MW or greater, represents a significant addition to the electric system. This type of PV generating station is becoming more common as large PV farms go beyond demonstration projects and become part of a utility’s renewable energy portfolio. There are already numerous sites in the 10-50 MW range and a few sites that are quite large. For example, California Valley Solar Ranch is a 250MW project currently under construction in San Luis Obispo County. PV Stations this large need to be interconnected with the transmission grid based on their size.

Large HPPV stations have their own unique characteristics. Interactions between the solar station and the electric system will depend on several factors and each will require its own unique modeling solution and basic considerations for the planner responsible for assessing the impact of large HPPV Stations on the grid. These are described below.

1.1.1.1 Location of Unit

The location of a large PV station will determine where it will be interconnected with the grid. The farther the PV station is from the electric facilities, the greater will be its cost to connect to the utility grid. Very large PV stations may require their own station or dedicated feeder, depending on the PV site location in relation to existing electric facilities. Large solar installations can have a positive effect on voltage control if ideally located on an existing feeder with properly coordinated control settings.

1.1.1.2 Size

The size and configuration of the PV station is critical to how it will be interconnected with the grid and what studies will be of concern. The larger the PV station, the greater will be its impact on the utility grid. This may require interconnection at the transmission level or other special equipment. Larger PV stations can be subject to greater voltage, power quality and frequency regulations. Smaller PV installations can sometimes be exempted from more elaborate protection and control schemes due to their more limited impact on the power system.

1.1.2 Numerous Small Distributed PV Sources

The addition of a large number of smaller PV stations distributed throughout the system or circuit will affect how the utility grid will interact and what studies will be of concern. A larger number of distributed PV sources will reduce the amount of output variability affecting the overall system, similar to a distribution system diversity factor. For PV installations, this comes from geographic diversity. Large numbers of small PV stations clustered in one area are subject to the same weather patterns and intermittency and can present the same concerns as one large PV station; though with somewhat less of an impact to the power system.

1.1.2.1 Number & Size of Units

The number and size of distributed PV sources will affect how the interconnections are performed and what needs to be studied. A large number of PV units on a distribution circuit could cause voltage control problems, voltage flicker, or other power quality issues on the distribution circuit. Higher penetrations of PV stations distributed on the grid could also have a positive impact as output fluctuations would be reduced as penetration levels increase.

A distribution of multiple, smaller PV installations can also be subject to fewer land acquisition and regulatory requirements. Distributed solar resources are also more easily integrated into public spaces such as utility poles, highway rights-of-way or the rooftops of public buildings. This trend has already begun in some areas of the country and is helping to hasten the adoption of solar power installations elsewhere.

1.1.2.2 Location of Units

The location of distributed PV sources will affect voltage control and feeder capacity. A large number of PV units on a single distribution feeder may cause havoc with voltage control and perhaps excessive transformer/regulator tap-changing operations back at the substation. There could also be wire capacity issues if the PV station output were required to reduce circuit loading from the substation.

1.1.3 Advanced Inverter Controls

The addition of PV stations with advanced inverter controls will affect the PV station model and how it responds to system disturbances. Advanced inverter controls with low-voltage ride-thru (LVRT) capability allow the PV inverter station to remain on-line during a temporary fault (down to a certain level) and subsequent protective actions, thereby preventing loss of load due to a load/generation mismatch. Advanced inverter controls also allow the PV station to contribute to system stability by providing the injection of reactive power into the electric power system. These are described in more detail below.

1.1.3.1 1 Quad vs. 4 Quad Inverters

Inverters are electronic power converters that can be used to couple dc or variable-frequency power sources to the electric grid. All PV stations depend on inverters for their grid connection. In these applications, the primary function of the inverter is to deliver the maximum real power generated to the grid. The early inverters were typically designed with only the basic controls necessary to perform this function.

Inverters also have a number of other control capabilities besides frequency conversion and real power delivery. As PV penetration levels increase and the rules for interconnection become more sophisticated, inverter control capabilities will be the key to successful implementation of large-scale PV generation.

When connected to an established power grid (where frequency and voltage are actively regulated), inverters basically operate as controlled current sources. The controlled inverter output current has several unique characteristics:

- Inverter impedance is very high (as seen from the grid). The inverter output current continues to follow the reference signal, even when power system faults cause large changes in voltage. This is quite different than a rotating synchronous generator, which can contribute relatively large transient current under faulted conditions.
- Inverter output current is limited. Output current from an inverter during a grid fault should not exceed 1.1 per unit. This level of fault contribution is negligible compared to conventional fault contributions from rotating machines or the transmission system. Inverter fault contributions can be considered negligible on the power grid.
- Inverter output current can be reduced to zero in a very short time. If necessary, the inverter controls have the ability to shut off the output current in less than 1 cycle. Inverter controls can autonomously initiate rapid shut down when abnormal grid conditions are sensed, or the controls can respond to a transfer trip signal.
- Inverter complex power output can be controlled in any of the four power quadrants. Real (P) and reactive (Q) components of the complex power can be directly and independently controlled. The active control of real power (P) allows power curtailment and power ramping, to be implemented in response to remote inputs (SCADA). Real power controls are expected to become essential functions for utilities with high-penetration PV, especially in smaller grids (island systems) where additional real power may not be acceptable and where frequency regulation is a concern. The inverter reactive power output can also be controlled and can be a valuable tool for utilities to regulate system voltage in high-penetration circuits or systems.
- Inverter reactive power output can be controlled rapidly. This automatic feature can be used in response to rapid system deviations, such as correction of voltage flicker.
- Inverters can absorb real power from the grid and deliver it to charge an energy storage device. This can facilitate implementation of an energy management system where the inverter supplies real power to the grid from the ES device when PV power is not available. The ES device could be designed to facilitate frequency regulation and power output leveling.
- Inverter output current can be controlled to correct grid harmonics. It would be costly and impractical to design a PV inverter to simultaneously deliver real power while also

serving as an active filter, but filter capability could be used off-peak when normal PV power output is at minimum.

- Inverter output can help correct unbalanced voltage at the point of interconnection

As PV penetration increases on the grid, advanced inverter control will become more of a necessity.

1.1.3.2 Inverter Control Operation

The operation of PV inverters in the field and their response to system disturbances can be enhanced with advanced inverter controls, as described earlier. Inverter operation and control settings that are determined by the utility planner to coordinate with other protective devices on the grid would enhance utility grid operations. Inverter control settings implemented by the PV Station operator without regard to utility grid interaction and coordination with grid the protection scheme would be the worst possible situation and could have catastrophic consequences.

1.1.4 Distribution Automation (DA)

Distribution Automation (DA) can improve how the system responds and is restored after a system disturbance. Inverter controls that can either ride-thru a short-term disturbance or be set to come back on-line automatically after switching has restored power to the circuit are being explored.

New inverters designed specifically for interconnection with the power grid enable more reliable utility operation with enhanced communication and control functions that support SmartGrid and DA functionality. Detailed PV inverter models will need to have the capability to select control features that mimic the behavior of DA control settings.

DA also involves voltage control, which is a control function of PV inverters, as described earlier. However, higher rated equipment will be needed to support additional reactive power flow into or out of the PV station.

1.1.4.1 Feeder Reconfiguration

Feeder reconfiguration through either distribution automation or physical reconfiguration by field personnel requires synchronizing capabilities to bring the PV station back on-line after a disturbance. With more intelligent inverters this can be an automated function. Automated switching can provide a benefit to the system in terms of faster restoration and enhanced reliability but difficult to build into a system model. The planning engineer will need accurate and realistic PV models to properly assess feeder operation and the resulting reconfiguration. The study of automatic distribution feeder reconfiguration via a time-series power flow with PV inverter output variability and PV controls modeled would allow the planner to evaluate voltage control interactions and operations on the distribution feeder, such as LTC, regulator, or capacitor switching.

1.1.4.2 Equipment Control & Operation

The operation and control of interconnection and system equipment will depend on a number of factors as previously discussed. PV output variability can cause excessive capacitor bank, voltage regulator or transformer load tap changer (LTC) operations, which can lead to higher maintenance costs or premature equipment failure. Enhanced PV monitoring and data communication can smooth the PV output fluctuation and prevent excessive equipment wear.

1.1.5 Energy Storage (ES)

Energy Storage (ES) could have a tremendous impact on the implementation of solar power on the electric grid. Energy storage has the potential to solve many of the output variability problems with PV sources. The PV model needs to have the ability to include energy storage systems to assess their impacts on the electric grid. The implementation of ES combined with PV generation has been shown in pilot projects to produce positive results in electric power system operation and performance.

However, this will also add complexity to the modeling requirements as the ES module of the PV model needs to be detailed enough to capture the effects of the ES device during transient simulations (less than 20 cycles).

1.1.5.1 PV Variability Mitigation

As described earlier, ES combined with a PV plant can provide smoothing of the PV station output, thus helping to solve the variability problems associated with intermittent cloud cover.

1.1.5.2 Load Shifting

If sized appropriately, a portion of the ES module could be reserved for load shifting. The energy produced by the PV station during off-peak hours could be captured in the ES module and then discharged during the peak load period to reduce system demand. Load-shifting in the right places on the electric grid could result in deferral of capital expenditures and savings for the utility.

1.1.6 Demand Response (DR)

Demand Response (DR) for a PV plant model simply acts to reduce the demand on the distribution circuit for a given input. This is usually in response to a system disturbance but could help reduce system or station demand when needed (see load shifting above and feeder loading below).

1.1.6.1 Type of Customers

The types of customers that might be connected to a PV plant and be participating in a DR program are usually commercial or industrial customers with a large rooftop or parking lot system. Integrating a large rooftop PV array with a commercial customer whose peak demand coincides with peak PV array output provides the most benefit for the customer. This reduces the customer’s peak demand and utility bill while providing a reduction in feeder demand for the utility and possible deferral of capital expenditures. Future PV models may need to have the ability to match predicted PV output with customer load for a given time step of the time-series power flow study.

1.1.6.2 Feeder Loading

The DR module of the PV model could trigger loads that need to be shed in real time to improve stability, either voltage or transient. This could also improve feeder loading by reducing load on the distribution circuit when needed and possibly defer capital expenditures for feeder capacity upgrades.

1.1.7 Interaction with Other Local Generation

The PV model needs to be able to simulate the interaction and effects with other local generation, whether conventional or renewable. There are long-term dynamic effects due to variable PV output and conventional feeder voltage regulation devices. To analyze those interactions, a time-series power flow study is required. There are also transient effects due to system disturbances that require a transient stability study. Therefore, the PV model needs to accurately reflect its long-term dynamic response characteristic in a time-series power flow study as well as its transient response in a traditional transient stability study.

1.2 HPPV Modeling Requirements for T&D Operation

As described earlier, a PV model needs to represent inverter characteristics for a wide range of T&D studies. A time-series power flow is the most critical application because of the time-varying nature of the PV station output. This variability creates problems for power system control and can result in excessive equipment operations. Models need to be able to simulate changes on the power system down to the minute as well perform simulations over an extended period of time, up to a full year.

The transient PV model is also required, but the effects of a PV station on the transmission grid is less severe than for the distribution system and will, therefore, be less observable. However, as PV penetration increases and larger PV farms become interconnected with the transmission grid, their total impact will on transmission system performance will become more observable.

1.2.1 Integrated Resource Plan

PV models for integrated resource planning need to be developed as well as standards for their use. These models will aid planners in making equipment and financial decisions regarding electric system improvements where PV plants are being considered.

It is possible that improvements in planning models can identify where PV stations would provide a positive impact on the grid, especially when combined with ES. These improvements have the potential to save the utility capital expenditures for improvements that would not otherwise be required. This may be accomplished with the implementation of advanced inverter control strategies, which then need to be incorporated in the PV models used for planning.

1.2.1.1 Load Shapes

Load shapes in 1-hour to 1-minute increments are needed to define the load requirements on the distribution circuit. This requires a minimum of 24 load flows (one for each hour) to analyze a 24-hour load profile. This provides the basis of the dynamic power flow study and reveals operating statistics for the distribution circuit, such as LTC or capacitor switching in a 24-hour period. These load shapes typically represent daily load patterns, but can also represent monthly or seasonal load variations or other adverse load conditions.

1.2.1.2 Load & PV Control

The PV station has the ability to reduce loading on the distribution circuit as well as provide voltage control, with the appropriate settings. The ability to model these features for interconnection studies is required for the planning engineer to make decisions regarding integrated resource planning.

Improved weather forecasting tools could also be merged with existing planning tools and used to predict the PV station output and circuit loading.

1.2.2 Transmission System Impacts

Large HPPV stations located on the transmission system will have an impact on transmission system performance and operation, and may impact Available Transfer Capability (ATC). It will certainly displace conventional generation somewhere on the system, which will affect transmission flow patterns. The Western Electric Coordinating Council (WECC) has recently formed a task force to develop generic, non-proprietary, positive-sequence simulation models of PV Stations for dynamic and power flow studies. These models will be used to study the impact of HPPV systems on the grid, both transmission and distribution. The models will be implemented in the General Electric PSLF and Siemens PTI/PSSE simulation platforms, which are the most widely-used transmission system simulation and analysis packages in North America. The ability to model HPPV stations in the power flow and stability platforms that are required for interconnection studies allow the planning engineer to make informed decisions regarding transmission interconnection requests and requirements for service.

1.2.2.1 Line Capacity

The ability to model HPPV stations in power flow software allows the planning engineer to make informed decisions regarding transmission line capacity and ATC. The addition of HPPV on transmission circuits could improve or reduce available line capacity, depending on their location in relation to grid flow patterns. Very large HPPV Stations also have the potential to enhance transmission operations by reacting to system disturbances with controlled inverter output characteristics.

1.2.2.2 Loss Savings

The addition of HPPV stations at the transmission level will affect power flows on the transmission system and losses associated with the power transfers. The addition of large

HPPV stations located closer to load centers could significantly reduce transmission system losses. The ability to model HPPV stations in the power flow software will make it easier to demonstrate and quantify these loss savings.

1.2.2.3 Reliability

In the initial phases of implementation, PV integration with the electric grid raised concerns about power system reliability. Sudden loss of PV station output (such as during cloud cover) would need to be made up from conventional generation and could have an adverse impact on a utility's reliability criteria for grid operation. The development of IEEE 1547 established requirements for PV integration with the electric grid as a direct result of those concerns as well as some others.

As more HPPV stations become a reality, distributed around the transmission grid, the overall reliability of PV station output would tend to improve because of the variance in geographic location.

Improvements in inverter technology will also facilitate the use of PV generation with the same level of reliability as conventional generation. The grid should still have the ability meet any n-1 criteria, however, including sudden loss of any HPPV station, which should be included in modeling considerations.

1.2.2.4 Voltage Constraints

Large PV stations can generally maintain a transmission level voltage under normal full operating conditions but not for severe disturbances on the power grid or under reduced PV output. Transmission load flow studies must meet certain voltage constraints that are in accordance with FERC guidelines and PV stations are generally not modeled to hold a voltage reference point. A dynamic PV model would allow the system planner to examine system performance in response to disturbances on the transmission grid with the PV station providing a desired output characteristic based on advanced inverter settings, described earlier.

Light loading conditions on the transmission grid are always a problem as voltages tend to be very high and it can be difficult for system operators to keep the voltage profile within FERC operating guidelines. High-penetration PV, with advanced inverter control settings, could help to maintain system voltage within these guidelines.

1.2.3 Distribution System Impacts

Large HPPV stations located on the distribution system will have an impact on feeder performance and operation. It will certainly displace conventional flow patterns on the feeder from the substation to the PV station location. The models currently under development by the Western Electric Coordinating Council (WECC) for transmission studies can also be used for some distribution studies. Based on a previous survey of software vendors (see previous report “End User Requirements”), there are some good distribution PV models being developed. Continued development of distribution-level PV models should be a major focus, since many of the PV installations (even high-penetration) are being installed on distribution systems. Impacts on the distribution system are greater than for transmission and many aspects need to be studied. These aspects are discussed in the following sections.

1.2.3.1 Capacity Margins (Peak / Off Peak / Seasonal)

Large HPPV stations located on the distribution system have the potential to greatly increase feeder capacity margins depending on location, season, and time of day. Conventional flow patterns on the feeder will be altered as the PV Station serves a larger portion of the load during peak sunlight hours. This may or may not coincide with feeder peak load. In some areas of the country, the summer feeder peak may actually occur after sunset when there is zero contribution from the PV Station.

For this reason, distribution feeders with large PV installations need to be studied over a 24 hour load cycle (matching the feeder daily load curve with the PV station output) to fully determine the capacity margins at various times. This can also apply to seasonal variations as there are more sunlight hours in the summer than in the winter, and feeder load patterns often shift seasonally. Typical daily feeder load and PV station output curves are shown below.

Figure 1 - Feeder Daily Load Profile and PV Station Output Curve

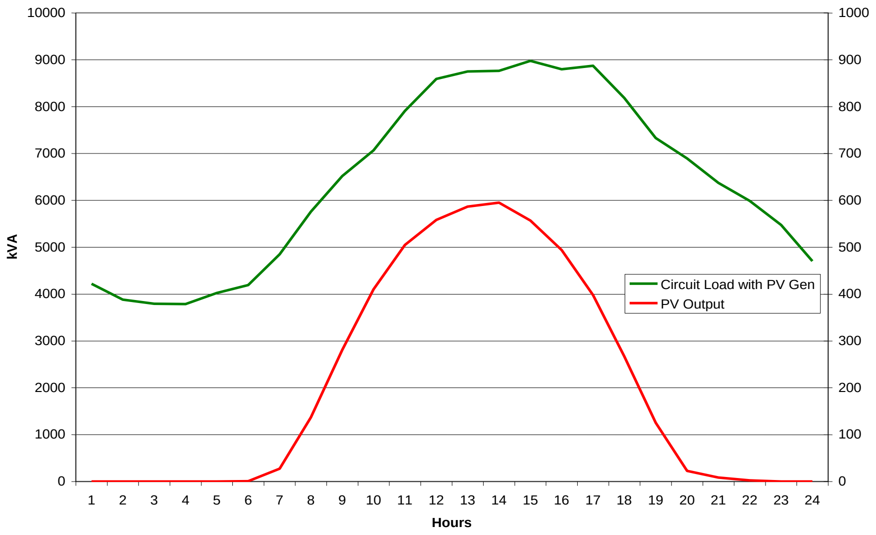
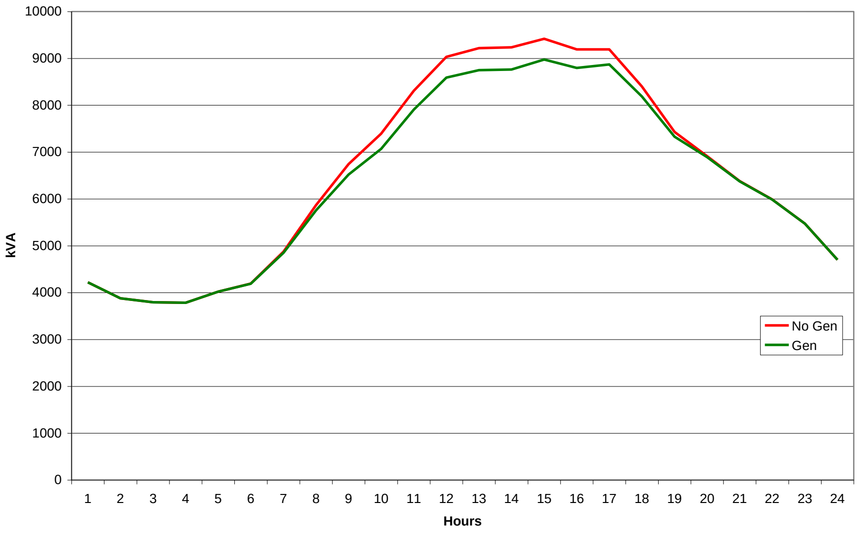


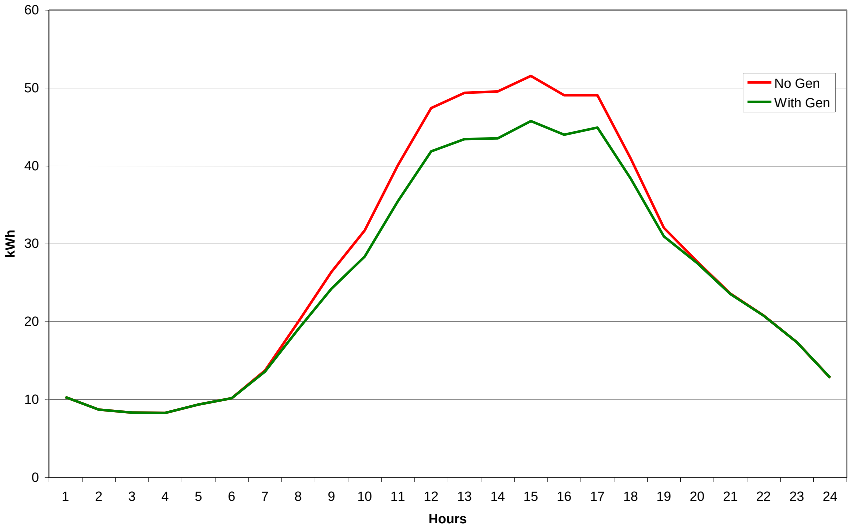
Figure 2 - Feeder Daily Load Profile with and without PV Station Output



1.2.3.2 Energy and Loss Reduction

High-penetration PV stations integrated with the distribution system, if located in the right place, may reduce feeder losses by displacing real power flow patterns on the feeder from the substation during sunlight hours. This will reduce annual system energy losses from the distribution feeder all the way back to thru the substation and transmission system during the hours of PV station operation.

Figure 3 - Feeder kW Losses with and without PV Station Output



1.2.3.3 Voltage Control

High-penetration PV stations on the distribution system also have the potential to improve feeder voltage control. Setting the PV station inverters to provide some reactive power output in response to variations in feeder voltage magnitude could improve overall feeder voltage performance, if properly coordinated with the station LTC or regulator. It also has the potential to cause unwanted and excessive station LTC operation if not properly coordinated. Also, as mentioned earlier, PV station equipment will need to be designed to accommodate additional reactive power flows. To assess feeder voltage performance with PV added, long-term dynamic load flow studies that include PV models with these control features are required.

1.2.3.4 Power Quality

The PV station inverters are a source of harmonics when located on the distribution system. This is a concern for utility planners, who are responsible for adhering to power quality standards. Most modern inverters individually meet power quality guidelines, but many inverters located together in a high-penetration scenario have the potential to exceed these limits and cause power quality problems on the distribution feeder. Programs that have the ability to analyze harmonic frequencies and their effects on the power system need to include HPPV model effects.

1.2.4 Protective Device Coordination and Safety

High-penetration PV stations located on the distribution system can cause protection and safety concerns for the utility. PV station protective equipment settings need to coordinate with those of the utility to limit reverse power flow in fault situations. Furthermore, if a fault located on the distribution system, were cleared by conventional utility relaying equipment, the utility lineman needs to be sure that ALL PV stations on that particular feeder are isolated from the faulted portion of the system and it is safe to work on.

1.2.5 Distribution Reliability and PV Islanding

High-penetration PV on the distribution feeder has the potential to provide a load-serving benefit under certain contingencies and thus improve reliability. Disturbances on the distribution feeder that remove the source could be coordinated with the protection system to allow the PV station to remain in service and serve a portion of the feeder load. This portion of system would be isolated from the remainder of the grid but remain in service as long as the PV station output matches or exceeds the isolated system load.

The National Renewable Energy Laboratory (NREL) High-Penetration PV Report[i] states that “In response to grid faults and / or loss of main source (islanding), immediately cease operation (per IEEE 1547). Upon islanding or faults on the interconnecting feeder, single facility generation can separate from the grid and continue supplying its’ own load.”

Although the frequency control feature already exists in PV inverters with battery storage, it is not typically implemented on most large scale PV inverters due to the cost of energy storage and the additional hardware required for simultaneous voltage and frequency regulation functions. The inverter protection methodology and fast / accurate islanding detection schemes have not been well established.

1.3 Conclusion

The basic requirements for a high-penetration photovoltaic (HPPV) model for T&D planning and operations assessments have been discussed in this report. It is essential that this PV model provide an accurate representation of large PV stations and their impacts on T&D system operation, including advanced inverter control features and dynamic behavior for grid interconnection studies. Future interconnection studies may necessitate a time-sequence load flow for a complete understanding of the voltage control issues involved on the Transmission or Distribution circuit being studied. To accommodate this, future PV models may require enhancements to include smart grid or DA control schemes and settings.

PV models and their application in system interconnection studies needs to conform to IEEE 1547, “Standard for Interconnecting Distributed Resources with Electric Power Systems”, as well as any other standards that may be affected by these developments.

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[i] Southern California Edison High-Penetration Photovoltaic Project – Year 1; NREL Technical Report – NREL/TP-5500-50875; June 2011