INTEGRATING HIGH PENETRATIONS OF PV INTO SOUTHERN CALIFORNIA

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ABSTRACT: California regulators recently approved a plan proposed by Southern California Edison (SCE) to install 500 MW of distributed photovoltaic (PV) energy in its utility service territory over the next 5 years. The installations will include 250 MW of utility-owned solar and 250 MW of independently owned solar. SCE expects that the majority of these systems will be commercial-scale rooftop PV systems connected at various points in the distribution system. Each of the SCE rooftop PV systems will typically have a rating of 1-3 MW. To understand the impact of high-penetration PV on the distribution grid, the National Renewable Energy Laboratory (NREL) and SCE brought together a team of experts in resource assessment, distribution modeling, and planning to help analyze the impacts of adding high penetration of PV into the distribution system. Through modeling and simulation, laboratory testing, and field demonstrations, the team will address the issues identified in the analysis by fully examining the challenges, developing solutions, and transitioning those solutions to the field for large-scale deployment. This paper gives an update on the project and discusses technical results of integrating a large number of distributed PV systems into the grid.

Keywords: grid integration, utilities, modeling

1 INTRODUCTION

The National Renewable Energy Laboratory (NREL), Southern California Edison (SCE), Quanta Technology, Satcon Technology Corporation, Electrical Distribution Design (EDD), and Clean Power Research (CPR) have teamed together to analyze the impacts of high-penetration levels of photovoltaic (PV) resources interconnected with the SCE distribution system. Specifically, SCE will be interconnecting a total of 500 MW of commercial-scale PV by 2015 within their service territory through a program approved by the California Public Utility Commission (CPUC). Research efforts under this project include:

- Development of distribution and PV system models required to evaluate the impacts of high-penetration PV
- Identification and development of the necessary distribution system studies and analysis appropriate for determining the impacts of high-penetration PV
- Data collection on study distribution circuits to quantify the impacts of high-penetration PV
- Development of high-penetration PV impact mitigation strategies in the form of advanced inverter functions to enable high-penetration PV interconnection
- Lab testing of advanced PV inverter functions
- Field testing of advanced PV inverter functions.

In the first year of the project, research efforts focused on:

- Identifying the needed PV system models and distribution system analysis tool capability
- Identifying prospective distribution circuits within the SCE service territory to be studied
- Understanding the challenges of integrating high-penetration PV levels into the SCE distribution system
- Identifying appropriate data acquisition equipment
- Investigating the capability of PV inverters to realize advanced inverter functions that may be useful for mitigating high-penetration PV impacts on the SCE distribution system [1].
2 FEEDER SELECTION AND OPERATION

Presently, two 12 kV distribution feeders that already include utility scale PV installations have been selected for inclusion in this project. Various feeder characteristics and existing/expected number of PV systems were considered as part of the selection criteria. The selected study feeders can also be defined as typical representations of 12 kV feeders for the SCE distribution systems, which have high PV penetration potential due to the type of commercial buildings with large roof-top areas suitable for PV installations.

The first study feeder, denoted as the Fontana, CA study feeder due to its approximate location, is a 12 kV feeder supplying an area with dominant commercial loads (Fig. 1) fed from a 66 kV substation. The feeder includes three switched (automatic) capacitor banks. The Fontana 2 MW roof-top PV system is the first roof-top PV installation by SCE constructed under SCE’s Solar Photovoltaic Program (SPVP). It is also expected that a total of 5.5 MW of PV generation will be added to the study feeder by the end of 2011. The Fontana PV system is electrically located close to the substation as it is at the end of an express feeder line section with a length of approximately one mile. The PV system is on the first part of the main feeder trunk before any branches and there are very few customers between the PV system location and the substation.

Figure 1. Schematic representation of the Fontana feeder

The second selected study feeder is located in Chino, CA and connects an existing 1 MW roof-top PV installation. This feeder is supplied from a 66 kV substation through a considerable length of the mainline feeder as shown in Fig. 2. This feeder is expected to include an additional 3 MW of roof-top PV, partly based on current installations as part of the SPVP program (0.75 MW) and additional PV installations presently in the interconnection queue (2.25 MW) based on power purchase agreements with independent producers.

SCE distribution feeders can be categorized in three voltage classes of 4.7 kV, 12 kV, and 21 kV. Most distribution substations are connected to either 66 kV or 115 kV high voltage systems. Among all distribution systems, the dominant category is 12 kV feeders supplied from 66 kV substations.

In a typical SCE distribution system, a load tap changer (LTC) is not used on substation transformers connecting to 66 kV systems. Substations connecting to 115 kV systems will be equipped with a LTC. Because all the distribution feeders of interest in this project are supplied from 66 kV substations, any effect of high-penetration PV installation on LTC operation may need to be investigated separately. The 115 kV LTCs typically regulate the voltage at the distribution bus (LV side of substation transformer) without load drop compensation. The reference voltage is typically set at 122 Vac with a bandwidth of ±1.5 V. The tap changer delay may vary in the range of 30 to 90 seconds, depending on the application and the coordination requirement with any downstream voltage regulator.

The SCE general practice is to install capacitor banks as required on distribution feeders as a preference to voltage regulators. In addition to substation-level capacitor banks (typically two banks), generally three or more capacitor banks may be found along the feeders to reduce the reactive power demand from high voltage systems (e.g. 66 kV and 115 kV systems).

Presently, SCE does not use any active voltage control on their distribution feeders. The near-future plan is also to optimize the set points for voltage regulating devices (LTCs, capacitor banks, voltage regulators, etc.) off-line and set them once at pre-specified values based on reactive power and loss conservation criteria. The set points may be revisited occasionally if there is any planned maintenance or modification to a feeder.

In general, to achieve conservation voltage reduction (CVR), SCE practice is to set capacitor banks and/or transformer taps to operate the distribution circuits at the lowest permissible voltage range of 114 V to 120 V. The objective is to passively reduce load and losses by operating at the lowest permissible voltage level.

3 DISTRIBUTION MODELING

As the penetration level of interconnected PV systems increases with a distribution system there is an accelerated need for both accurate models of the solar resource and advanced distribution system analysis tools to evaluate high-penetration PV system impacts. This report provides initial assessments of solar resource data for use in distribution system studies and addresses the capability of existing distribution system modeling tools. Modeling needs in support of this high-penetration project will be broken into utility distribution modeling and solar side modeling.

The following are general utility concerns or issues to be addressed with interconnecting a distributed resource (DR) with a utility system. These concerns are broken into the need for quantifying the impacts of DR on protection, operation, and planning and engineering studies.

From a protection point of view software capabilities need to address loadability, selectivity, and sensitivity, with the following definitions:

- **Loadability** – ability to serve load without tripping.
- **Selectivity** – the system protective devices nearest the fault isolate the fault before more remote device(s) operate to isolate the fault.
- **Sensitivity** – the ability to sense faults.

Figure 2. Schematic representation of the Chino feeder
The following are examples of concerns that need to be studied:

- Improper coordination, nuisance fuse blowing, and upstream single phase faults resulting in fuse blowing
- Close-in faults causing voltage dips that trip DRs, isolating DRs from upstream faults
- DR stability during faults, islanding, reclosing out of synchronism, and transfer trip
- Equipment over-voltage, switchgear ratings, under-frequency relaying, and distribution automation studies.

From an operational point of view, software capabilities need to address the following concerns:

- Equipment over-voltage, resonant over-voltage
- LTC regulation affected by DRs, voltage regulation malfunctions, and line drop compensators fooled by DRs
- Substation load monitoring errors
- Loss of exciters causing low voltage, self excited induction generators, in-rush of induction machines causing voltage dips, voltage cancelled by forced commutated inverters, and capacitor switching causing inverter trips
- Cold load pickup with and without DRs, flicker, harmonics, stability during faults, and long feeder steady state stability
- Switching impacts resulting from large levels of solar generation
- Not allowing DRs to limit system operations during normal and emergency conditions including switching operations
- Protection and coordination with inverters, including sectionalizer miscounts
- Interoperability of multiple inverters from various manufacturers and voltage control with multiple sources on a distribution feeder
- Forecasting/planning for peak and light load
- Reliability impacts on both momentary and forced outage rates
- Economic impacts on operations energy and capacity
- Financial impact on capital and O&M.

From a planning and engineering point of view, software capabilities need to address the following concerns:

- Feeder loading criteria and forecasting
- Load forecasting that considers multiple generation sources
- The amount of generation that can be installed on a distribution feeder
- Feeder design that considers large levels of DR generation
- Distribution planning models that reflect actual system operation with high levels of DR generation
- Dynamics of small generators
- Economic analysis of losses
- Generation planning and operation for both capacity and energy, including production profile throughout the year and type of production.

In addition to new analysis tools, training for engineers that will use the new tools will be important to the overall success.

4 DATA AQUISITION

SCE utilizes a data streaming and historian tool that logs rms voltages at the distribution substation as well as the rms current and reactive power of each feeder. The total substation current (in Arms) and reactive power of the transformer is also monitored. This information is typically logged at 10-second intervals as soon as a pre-specified level of variations in voltages or currents occurs. The data resolution at substation level also can be increased to 4-second intervals.

In addition to substation data, several voltage monitoring points along the feeder are available, mainly at capacitor bank locations. The capacitor bank voltage is captured for the only phase that has a connecting single-phase PT and used by the capacitor bank controller. The capacitor bank on/off status is also reported upon changes.

One of the applications of data monitoring and measurement is to verify feeder models, and typical phenomena may be observed during simulation studies.

5 ADVANCED INVERTER TECHNOLOGY

PV systems use inverters to connect the DC power produced by PV arrays to the AC power of the electric power system. Electric utilities have viewed the advent of these inverter interfaces with a certain amount of fear, both because of their unfamiliar operating characteristics and because of their location in distribution systems where there traditionally has been minimal power generation. The level of concern has increased with the rapidly increasing size of proposed projects relative to the feeder rating and/or the minimum load levels. It is of course perfectly feasible to generate power in new or existing distribution circuits, and even to export power back into the transmission system, but in so doing we challenge some of the traditional assumptions that have been made in the design of protection and voltage regulation schemes for these circuits. This is especially true in the case of higher penetration levels for PV generation.

These concerns can be roughly grouped into three categories as follows:

1. What will be the effect of fluctuating real power output from renewable sources on the normal operation and power quality of the distribution system?

   • Increased switching operations for line regulators, tap changers, switched-capacitors.
   • Steady-state voltage regulation over the range of real power generation, especially on long feeders.

2. Should PV generators be allowed/required to participate in voltage regulation automatically, or on the basis of reactive power dispatch or scheduling? If autonomous local automatic voltage control is allowed, can stable operation be expected when multiple PV generators are involved on the same feeder? Will fast...
automatic voltage controllers "fight" with slower line regulators?

- Flicker due to rapidly fluctuating voltage caused by sudden changes in real power generation.
- Transient voltage changes on sudden trip of PV generation system, especially if the system is actively participating in voltage regulation.
- Harmonics generated by the PV inverters, and possible resonant interactions of inverters with the distribution system.
- Conductor and equipment loading due to new power flows resulting from the introduction of local power generation in the distribution system.

3. How should the protection relay schemes be changed and/or designed for existing and new distribution feeders when new generators are connected?

- Reversible real and reactive power flows possible.
- Protective relay settings and operation.
- Contribution of new generators to short circuit levels.
- Islanding of generators with residual load connected.
- Auto-reclosing feeder breaker onto energized generators.
- Appropriate grounding schemes for new generators to allow ground fault detection and prevent transient over-voltages.

Additionally, there are concerns about providing real power management for frequency regulation in smaller grids (e.g., islands) with limited aggregate generator rotational inertia.

- Rapid curtailment of real power sources on over-frequency.
- Rapid load-shedding and/or "spinning reserve" deployment on under-frequency.
- Ramping of real power from variable sources to minimize impact on the grid frequency.
- Transient frequency excursion on sudden trip of generating system.

Many of these concerns can be addressed through a proper understanding of the capabilities and operating characteristics of the modern inverters that are used to couple PV systems to the grid. Most of the issues listed as concerns do not in fact present fundamental obstacles to the implementation of high penetration levels of PV generation, and in many cases the presence of inverter-based PV generation can facilitate solutions rather than complicate the problems. This is especially true in regard to the area of system protection, because inverters are inherently fast acting and current-limited.

Inverters are electronic power converters that can be used to couple dc or variable-frequency power sources to the grid. Practically all renewable power generation systems depend on inverters for their grid connection. In these applications, the primary function of the inverter is simply to deliver the maximum possible generated real power (P) as efficiently as possible to the grid. The first generation of inverters for PV power was typically designed with only the basic controls necessary to perform this primary function, while complying with UL 1741 and IEEE 1547 requirements. For low power levels (less than 500 kW) and low levels of PV power penetration, certification of the equipment to these standards was sufficient for utilities to allow interconnection with the grid without much concern.

In addition to frequency conversion and basic real power delivery, inverters also have a number of other inherent control capabilities that are widely used elsewhere in power systems for power management and power quality improvement. As the penetration levels increase for PV generation, and as more sophisticated rules for interconnection emerge, it has become clear that harnessing these inverter control capabilities will be key to the successful implementation of large-scale PV generation in distribution systems. Consequently, a wide range of control functions have already been incorporated into newer PV inverter designs that will allow them to play an important role in the operation of the distribution system. The most relevant inverter capabilities and the ways in which they can facilitate the successful implementation of high penetration levels of PV generation are listed below.

- Control of real power limit (curtailment)
- Controlled ramp rate for real power limit
- Control of reactive power output or power factor.

6 FUTURE PLANS

This project will continue the analysis of high penetrations of PV on distribution feeders in the Southern California Edison service territory. New inverters with advanced functionality will be installed in the circuits in order to increase the amount of penetration on the test circuits.

7 SUMMARY

This paper summarized the first year efforts of a study on high PV penetration in Southern California. Two study distribution circuits were identified and discussed in terms of the expected PV penetration levels attained as SCE builds out the 500 MW of installed PV within their service territory. To properly simulate high-penetration PV operation on a distribution circuit, the expected solar resource of a given PV installation needs to be determined. This paper describes the additional functionality required of the distribution system modeling software package itself to properly and effectively evaluate high-penetration PV scenarios. Data acquisition systems needs and locations were discussed. The additional inverter functionality that will be implemented in order to specifically mitigate some of the undesirable distribution system impacts caused by high-penetration PV installations was described.

8 REFERENCES