



High Penetration Photovoltaic Case Study Report

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National Renewable Energy Laboratory

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Introduction

Technical concerns with integrating higher penetrations of photovoltaic (PV) systems include grid stability, voltage regulation, power quality (voltage rise, sags, flicker, and frequency fluctuations), and protection and coordination. The current utility grid was designed to accommodate power flows from the central generation source to the transmission system and eventually to the distribution feeders. At the distribution level, the system was designed to carry power from the substation toward the load. Renewable distributed generation, particularly solar PV, provides power at the distribution level challenging this classical paradigm. As these resources become more commonplace the nature of the distribution network and its operation is changing to handle power flow in both directions.

A large portion of distribution system components, including voltage regulators and protection systems, were not designed to coordinate with bidirectional power flow and bidirectional fault currents from distributed generation and PV systems in particular. Coordinating these devices in the presence of high penetration PV areas introduces additional challenges to feasibility and system impact studies. Some cases require modification of existing protection schemes, additional distribution equipment, or reactive power requirements on the PV inverters.

This report is focused on large PV installations in which penetration is significantly greater than 15% of maximum daytime feeder load. To date the impact on the electric utility and its customers has not been problematic in any of these cases. The PV system installations described in this report exceeds what most experts consider high penetration scenarios. The voltage, power quality, and other operating parameters have been maintained within the required ranges with minimal negative impact on distribution operations and utility customers. These case studies are intended to demonstrate success stories with integration of large PV plants at the distribution level as well as some of the solutions used by the utility to ensure safe, reliable operation of both the PV system and the distribution network.

1 Case Study: 10 MW Plant near Carlsbad, New Mexico

System Highlights

System Owner:	SunEdison
Utility:	Xcel Energy
System Integrator:	SunEdison
System Size:	9.9 MW _{DC}
Network Type:	Radial, Dedicated Feeder for PV Plant
Special Interconnection Requirements:	<ul style="list-style-type: none">• Fixed power factor to avoid high voltages• Inverters required to energize incrementally

Introduction

This PV plant is a 10 MW ground mount facility located near Carlsbad, New Mexico. It is connected in the distribution network 0.75 miles from the substation on a dedicated branch of the feeder. It is located within Southwestern Public Service Company's service territory. Southwestern Public Service Company is a subsidiary of Xcel Energy.

Information for this case study was compiled from data provided by Xcel Energy's distribution engineers responsible for the applicable circuit, from Xcel Energy's published reports, and manufacturer data sheets.

System Overview

Utility: Xcel Energy is an investor-owned utility serving several states in the midwest and west. Its service territory includes portions of Michigan, Wisconsin, Minnesota, North Dakota, South Dakota, Colorado, New Mexico, and Texas. Southeastern New Mexico and northwest Texas are served by Southwestern Public Service Company. Southwestern Public Service Company serves about 350,000 customers and one million people across its territory.

In 2011, Southwestern Public Service supplied about 4,700,000 MWh to customers. New Mexico's rule 572 requires that a public utility source 10% of its retail energy from renewable sources. Additionally at least 20% of these renewable source are required to be solar generation and at least 1.5% distributed generation.¹ The Carlsbad PV Plant helps to satisfy these goals.

PV System: The Eddy County PV plant is a 9.9 MWDC facility owned by SunEdison. It is located 0.7 miles west of the intersection of Old Cavern Highway and Hopi Road near Carlsbad, New Mexico. The plant is connected to a distribution feeder 0.75 miles west of the substation. This plant was commissioned on August 5 2011.

The PV panels are Trina TSM270PC14 cells with a max DC output power of 270 Watts (W) at standard test conditions (STC). The manufacturer stated efficiency of these modules is 13.9% at STC.² These modules are ground mounted and use a single axis tracking system. These PV modules feed a set of Power One inverters which includes three types of inverters: the PVI-330-TL-EN, PVI-275-TL-EN, and PVI-220-TL-EN. These inverters are 330, 275, and 220 kWAC units respectively.³

¹ Southwestern Public Service Company -- 2011 Annual Renewable Energy Portfolio Procurement Plan, <http://www.xcelenergy.com/staticfiles/xcel/Regulatory/Regulatory%20PDFs/CLB-22011RPSPlanfor2013.pdf> Xcel Energy. July 1, 2011

² Trina Solar TSM PC-14 Datasheet. http://www.trinasolar.com/images/PDF/datasheets/us/TSM-PA14_US.pdf Trina Solar. 2011.

³ Power One PVI Inverter Series Datasheet. http://www.power-one.com/sites/power-one.com/files/pvi-55.0...330.0_en_2.pdf Power One, 2011.

Distribution Network: The PV plant is served by the Hopi Substation, located at the intersection of Old Cavern Highway and Hopi Road near Carlsbad, New Mexico. The PV system is 0.75 miles from the substation on 336ACSR conductor. A one-line diagram of the distribution network and the PV system is given in Figure 2-1.

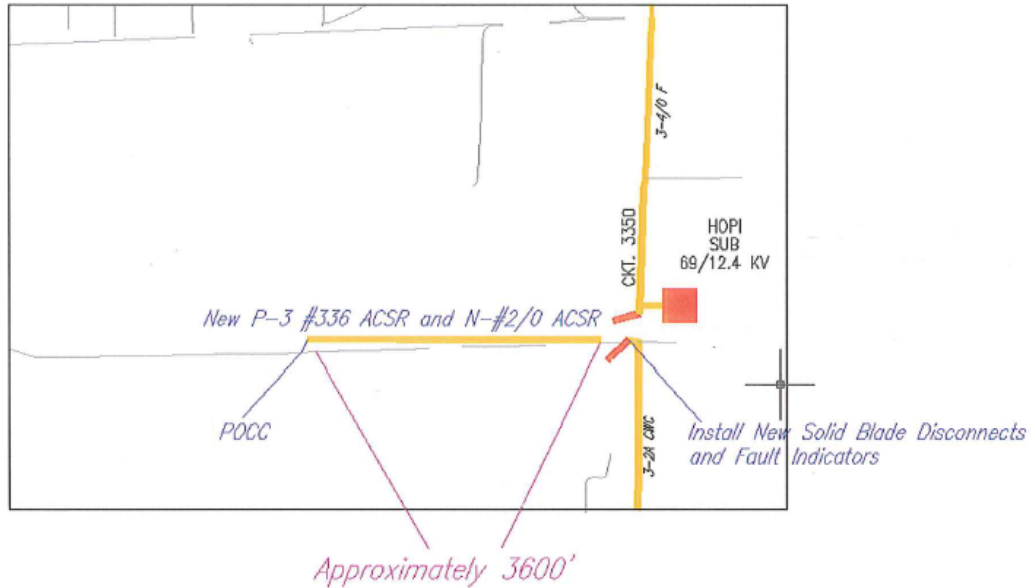


Figure 2-1: Carlsbad, New Mexico PV System, Substation, and Distribution Circuit

The Hopi Substation operates at 69 kV on the transmission side and 12.47 kV on the distribution side. The transformer in the substation is rated at 28 MVA. Voltage regulation on this distribution system is handled by a load tap changer located on the substation transformer and switched capacitors on the feeders.

The peak load on this substation exceeds 10 MVA. The minimum daytime load on the substation is about 3.87 MVA. No other distributed generation (DG) is located on this feeder or substation. Since no other DG is present, the penetration level is determined by the single PV plant. The 9.9 MVADC rating of the plant is close to the typical peak load of 10 MVA and thus the PV penetration level, defined as total installed PV divided by max load, would be in the 90% to 100% range. During minimum daytime load times the PV system power output can exceed the load on the substation.

Interconnection of the PV System

System Impact Studies: Given the size of this PV system in relation to the load and substation, Xcel Energy had several concerns prior to interconnection of the system. As clouds or other solar transients move across the PV array, the output power necessarily drops. If the PV is acting as a major source on the distribution circuit, this power loss can have the effect of depressing the voltage. A sudden drop in distribution voltage resulting from passing clouds was a major concern for the utility. Additionally, the effects of

system energization and de-energization with regards to voltage and power flow were also a concern. Xcel Energy was also concerned about the changes in steady-state voltage profile along the circuit and desensitization of substation protection relays with the additional power injections.

In order to address these concerns, Xcel Energy's distribution engineers performed several studies prior to interconnection of the PV plant on the Hopi Substation. These studies included fault current contribution, protection coordination, voltage delta, and voltage profiling studies. These studies were primarily performed in the SynerGEE distribution modeling software package.

The protection coordination studies identified desensitization of relaying at the substation as a potential problem resulting from the addition of the PV plant, and additional line protection was added to address this issue. Voltage supervised reclosing was added to the substation breakers because the load flow studies identified potential problems given the size of the PV system and expected minimum loading on the distribution circuit. The load flow studies also indicated that high voltages may result from the PV interconnection; consequently the PV owner was required to regulate their output power factor to a fixed, leading value. Additionally the PV owner was required to energize the inverters incrementally in order to avoid large voltage steps.

Distribution System Upgrades: In anticipation of the new PV system, two reclosers were added to the distribution feeder. The utility also installed 0.75 miles of 336ACSR conductor to provide a primary distribution feeder from the substation out to the PV system. This conductor was sized to handle full solar production from this PV plant. Additionally, the substation protection schemes were upgraded to include voltage supervised reclosing and extended line protection as mentioned above. No additional issues requiring equipment upgrades were identified after interconnection of the PV system.

Effects of the PV System

Many of the issues identified by the interconnection studies have been observed on the distribution system after commissioning of the PV plant. The mitigation steps and system upgrades detailed above have prevented these issues from having adverse effects on the distribution system and feeder. No additional protection issues have been observed since the connection of the PV plant.

Xcel Energy engineers have not observed any reverse power flows in collected data, but expect that, given the size of the PV system and the load, power sometimes flows up to the 69 kV transmission level when the PV is at full output and the local load is relatively light. These occurrences have not produced any reportable problems to date.

Conclusions and Ongoing Studies

Utility Perspectives: Results from this system and other 10 MW-scale PV plants in west Texas and New Mexico have helped to guide Xcel Energy in performing impact studies and approval of interconnection requests. Xcel Energy now strongly encourages that PV

plants which are to be attached on 15 kV class distribution feeders and are 10 MW or larger be located within 2 miles of the substation. Currently, the furthest 10 MW scale plant in this region is located 1.7 miles from the substation on a 556AA conductor.

Continuing Studies and Research: No additional studies have been performed on this circuit since the interconnection process. As the circuit is operating without issue, they have not been necessary to this point. This circuit will be re-evaluated on a periodic basis to ensure that it is operating correctly. Operational experience and collected data will necessarily inform and direct these studies. Currently, no research projects are focusing on this PV system or distribution network.

2 Case Study: Colorado State University Foothills Campus, Fort Collins, Colorado

System Highlights

System Owner:	Colorado State University
Utility:	<ul style="list-style-type: none">• Xcel Energy• Public Service Company of Colorado
System Size:	5.2 MW _{AC}
Network Type:	Radial
Special Interconnection Requirements:	<ul style="list-style-type: none">• Inverters required to energize incrementally• Required to set inverters to absorb 100 kVAr or 150 kVAr at utility request to avoid high voltages



Figure 3-2: PV System at Colorado State University Foothills Campus

Introduction

Xcel Energy owns and operates the distribution circuit described in this study where this is approximately 47% PV penetration. 5.2 MW of PV is installed on the Colorado State University (CSU) Foothills Campus, on the western edge of Fort Collins, Colorado.

Xcel Energy's primary concern with the installation of this PV system is maintaining voltage levels within ANSI C84.1 (range A). The PV system was built in two phases. After completion of Phase I, a 2 MW installation, there were no measured voltage or power quality aberrations. Phase II added 3.2 MW of additional PV, and the voltage and power quality parameters remained within acceptable levels.

System Overview

Utility: Overall, Xcel Energy is ranked as the fifth highest in installed solar system rated capacity according to the Solar Electric Power Association, and first in wind energy according to the American Wind Energy Association. The regulated Xcel Energy operating companies operate in eight states (Colorado, Michigan, Minnesota, New Mexico, North Dakota, South Dakota, Texas, and Wisconsin) with approximately 3.4 million electric customers and 1.9 million natural gas customers. The operating company in Colorado is Public Service Company of Colorado (PSCo).

PSCo has 74 MW of PV interconnected to distribution circuits and substations, for a total of over 7,000 systems. PSCo has 1,260 MW of wind power providing about 10% of the PSCo energy sold in Colorado, and has plans to add an additional 700 MW of wind power by 2013.

In particular, solar installations in the form of PV systems have been increasing due to substantial financial incentives in Colorado. Xcel Energy has provided a significant portion of the funding for the project through its Solar Rewards program.

In the major states it serves, Xcel Energy is required to comply with state Renewable Portfolio Standards, implemented in part to reduce carbon emissions. In Colorado, Xcel Energy has a compliance requirement for distributed energy resources (DER) and provides customer and developer incentives for the deployment of PV systems. Xcel Energy has established requirements for DER interconnections and, provided the interconnection meets specific standards (based on IEEE 1547), allows them as long as the grid can reliably accept the new generation sources. Xcel Energy reviews all proposed DER interconnections.

PV System: The PV system installed at the CSU west campus is one of the largest PV systems in Colorado and one of the largest PV systems on a university campus.⁴ The energy produced will offset about one-third of the energy requirements for the CSU west campus over the next 20 years. The PV system covers 15 acres, and utilizes both single-axis tracking and fixed-axis PV arrays. The CSU PV system was built in two phases, with a total peak rating of 5.2 MW. Phase 1 was completed in 2009 using Trina Solar

⁴ <http://www.news.colostate.edu/Release/4991> See press release from Colorado State University.

crystalline-silicon PV modules, Array Technologies Wattsun single-axis tracking system, and Advanced Energy Solaron inverters. Phase 2 used the same modules and inverters, but utilized a fixed mounting system for the arrays.

Distribution Network: The CSU Foothills Campus is currently supplied by an Xcel Energy distribution feeder (13.2 kV) that is 6.5 miles in length. The substation is served by 115 kV on the high-voltage side stepped down to 13.2 kV for the distribution voltage, with the substation transformer being a 24 MVA oil-cooled unit. The feeder’s average daily peak load was 7.5 MVA in 2010, with a peak demand load of 9.1 MVA and a minimum daytime load of 3.1 MVA.

Figure 3-2 is a one-line diagram of the Xcel Energy substation and distribution system, and illustrates the components of the circuit as well as the 2 MW and 3 MW PV systems.

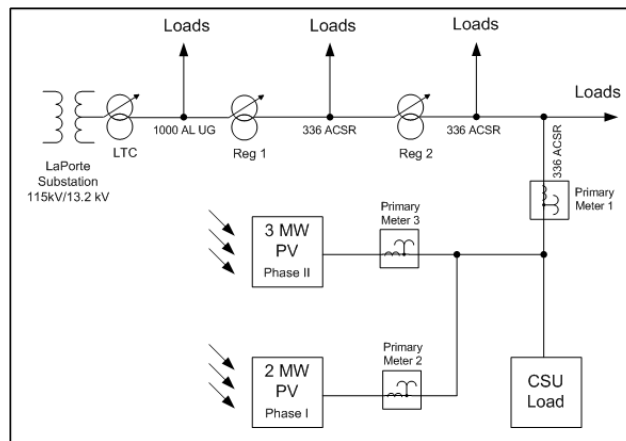


Figure 3-3: One-line Diagram of the Xcel Energy Distribution System, PV Systems, and Loads

The CSU Foothills Campus will eventually be served by a new substation located on the campus footprint. The new College Lake Substation will be supplied by the Platte River Power Authority-owned 230 kV transmission system and will serve the CSU Foothills Campus at 13.2 kV.

Figure 3-3 illustrates the load profile of the distribution feeder to which the PV system is connected during one week of February, 2011.

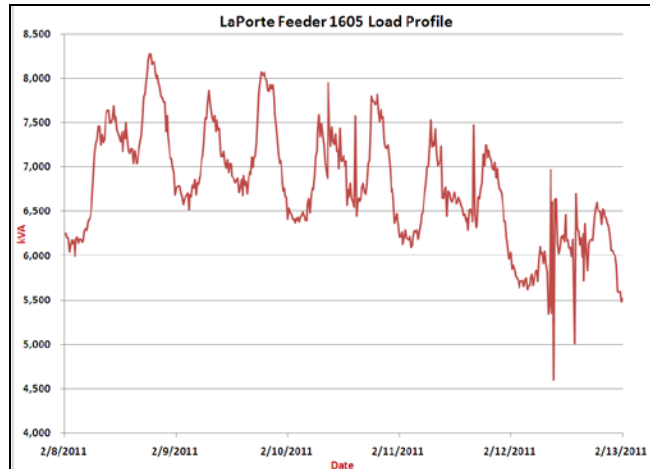


Figure 3-4: Load Profile of Distribution Feeder

Interconnection of the PV System

System Impact Studies: Xcel Energy engineers completed both a feasibility study and a system impact study for the PV system installation. Engineers used a distribution simulation analysis package to evaluate the performance of the distribution feeder, loads, and PV systems prior to the installation of Phase 1 and once again prior to Phase 2.

One of the potential problems identified by these impact studies was that high voltages may occur during periods of light feeder loads and high PV system production. If high voltage becomes a problem, Xcel Energy has planned a four-step mitigation approach which progresses through mitigation options until the problem is rectified.

1. Adjust the voltage regulators to stabilize the voltage levels.
2. The inverters (10 total) will be configured to absorb 100 kVAr each.
3. The inverter configurations will be changed so they will absorb 150 kVAr each.
4. Xcel Energy will notify the system operator to disconnect all or part of the PV system and install an additional power factor controller or dynamic VAR compensator.

System Voltage: Xcel Energy is primarily concerned about system voltage fluctuations on any large PV installation, including flicker and high or low voltage levels and excessive regulator and load tap changer (LTC) operations. Tools to address voltage aberrations include:

1. LTC at substation transformer for voltage regulation
 - LTCs have the capability to buck or boost voltage, typically through steps covering a total of 10% of the source side voltage, and are controlled at the substation level automatically, manually, or on occasion set via SCADA.
2. Voltage regulators on the distribution feeder (some with advanced controls)
 - Regulators can buck or boost voltage and may be bi-directional.

- Regulators can use sophisticated controls to maintain voltage levels several miles from the regulator banks, typically using an X/R scheme.
 - A tool used in some locations is the use of directional setting groups for bi-directional regulators. This requires different settings depending on the direction of current flow, and may be used in higher penetration circuits.
3. Capacitor bank (with remote controllability)
 - Capacitors will raise voltage levels in most cases, and their use with large PV systems on the same feeder must be controlled carefully. Many distribution circuits employ fixed capacitor banks, and are often used to inject VARs onto a circuit.
 4. Inverters having power factor control capability
 - Some newer models of inverters, such as the *Advanced Energy Solaron* inverters used in this installation, may be programmed to supply VARs. Ultimately, a power factor control would be the preferred method to maintain voltage stability once equipment is available. The capability of supplying VARs is in conformance with IEEE 1547 and UL 1741; however the use of reactive power must be coordinated with the electric utility engineers.

Voltage Regulators on LaPorte 1605: There are two sets of 15 kV class voltage regulators on the feeder, which were in operation prior to the PV installation. The voltage regulators closest to the CSU campus (Reg 2 on Figure 3-2) have been programmed to maintain a 1 Volt (V) bandwidth (on a 120 V base) at the campus service entrance point. This tight bandwidth was initiated before the PV system was installed, primarily due to the configuration of some un-grounded wye transformers on the campus. Maintaining a tight voltage bandwidth has created a situation where the regulators have operated hundreds of thousands of times over a one year period. Two of the regulators were found to be non-operational when checked during normal maintenance procedures, and had to be rebuilt by Xcel Energy technicians. Those failures, while unfortunate yet predicable, did not create complaints by utility customers on the feeder.

Staggered Energization of Inverters after an Outage: Energizing the CSU circuit by the inverters must be staggered so that only one inverter comes online at a time. The inverters were programmed to connect to the grid in intervals (typically after an outage has caused the system to cease to energize). This staggered re-energization will minimize the potential of 5.2 MW in PV generation coming online too quickly and causing a voltage swell.

Table 3-1 shows the inverter's staggered start-up scheme for the reconnect time after any PV system trip.

Table 3-1: Start-up Scheme for PV Inverters

Inverter No.	Start-up time	Inverter size
1	230 seconds	500kW
2	260 seconds	500kW
3	290 seconds	500kW
4	320 seconds	500kW
5	350 seconds	500kW
6	380 seconds	500kW
7	410 seconds	500kW
8	440 seconds	500kW
9	470 seconds	500kW
10	500 seconds	500kW

Distribution System Upgrades: A new distribution substation is being constructed within one mile of the 5.2 MW PV system and campus load, and was completed during the summer of 2011. Building a multi-megawatt PV system adjacent to a substation is understood to have a significantly lower impact on a distribution feeder compared to PV systems located miles from a substation. This is due to lower impedance between the PV system and the substation transformer, higher available fault current due to the proximity to the substation and greater system stiffness factor, resulting in additional operational advantages desired by CSU.

Effects of the PV System

Exporting and Non-Exporting PV Systems: Much of the power generated by the 5.2 MW PV systems is consumed at the university campus. However, there are times when the PV system generates more power than the campus can consume and the PV system exports power back to the Xcel Energy distribution feeder where it is consumed by neighboring loads. Figure 3-4 indicates power levels measured at the campus primary meter. Any PV system which exports power back to the utility system has the capability to create a high voltage condition if not properly addressed by the utility distribution engineers. Both exporting and non-exporting PV systems have the capability to create voltage flicker with passing clouds.

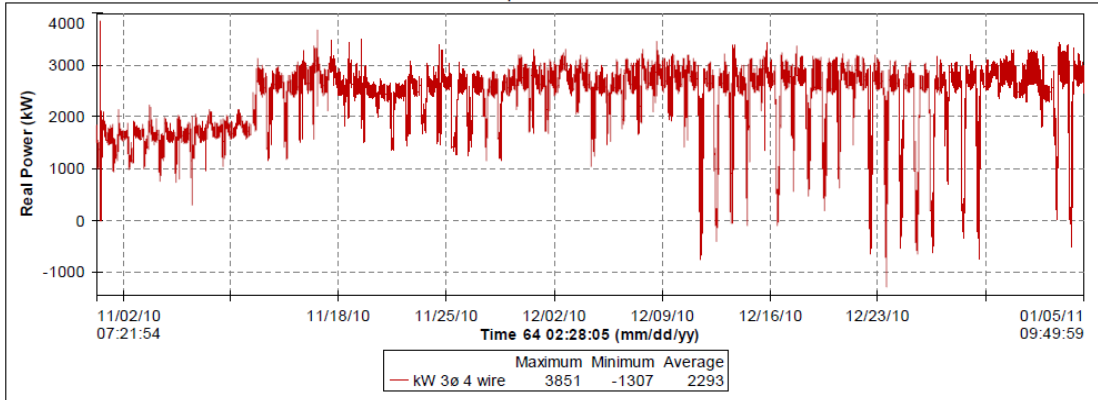


Figure 3-5: Real Power Measured at the CSU West Campus, which includes the PV System Generation

Note the times when power drops below zero, which are times when power is being exported to the utility distribution system.

Power Quality: Voltage, harmonics, flicker, and other power quality measurements have been in the acceptable range and there have been no complaints from customers following the installation of the PV system. This was verified on several occasions (see Figure 3-5) by having Xcel Energy technicians set power quality recording devices at the primary metering locations and recording voltage, current, harmonics, etc.

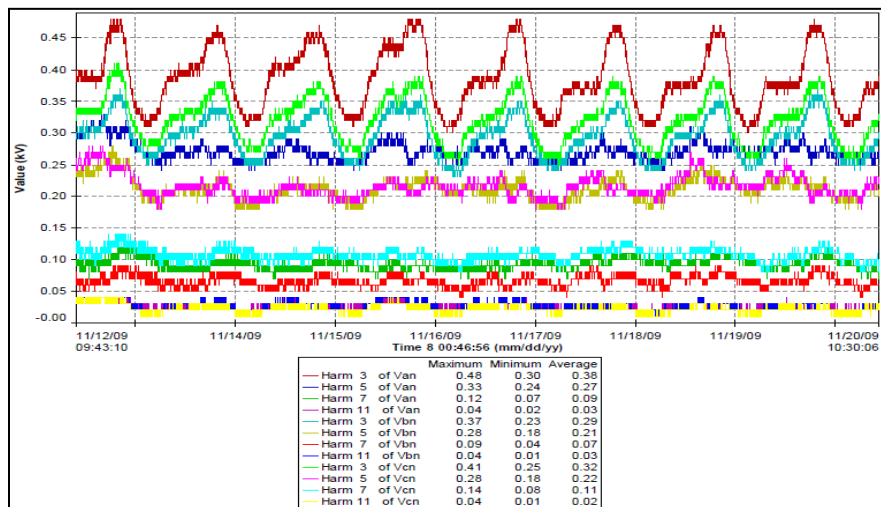


Figure 3-6: Harmonic Analysis at the Primary Meter Serving Load and the PV Systems

Although the distribution feeder has very high levels of penetration, well in excess of the 15% threshold considered high penetration, the electric distribution system generally operates within normal parameters and without any significant customer complaints or customer equipment failures due to power quality problems.

Conclusions and Ongoing Studies

Utility Perspectives: The installation of the PV on this circuit has not had any significant effects on the day-to-day operation of this system. All power quality issues including flicker, harmonics, sags, and swells have been within acceptable ranges and, for the most part, unnoticeable. Utility concerns about elevated voltages on the circuit have been somewhat alleviated by the mediation steps put in place and through operational experience. However, the fixed leading power factor approach outlined above was taken as an interim step until additional planned distribution system architecture was installed. Although successful, it was not intended as a long-term solution.

Continuing Studies and Research: Currently no major research projects are studying the PV system or feeder. As with all of their circuits, PSCo will review the operation of this circuit on a periodic basis to ensure that it is operating correctly and there are no voltage, power quality, or protection issues. They are currently collecting Supervisory Control and Data Acquisition (SCADA) data for this circuit as well as power quality data.

3 Case Study: Kapa'a Solar Project, Olohena Road, Kaua'i, Hawaii

System Highlights

System Owner:	Kapa'a Solar LLC
Utility:	Kaua'i Island Utility Cooperative
System Integrator:	REC Solar, Inc.
System Size:	1.2 MW _{DC}
Network Type:	Radial
Special Interconnection Requirements:	None



Figure 4-7: 1.2 MW_{DC} Photovoltaic array on Kaua'i, Hawaii (Credit J. Keller, NREL)

Introduction

In late 2005, the Kaua'i Island Utility Cooperative (KIUC) updated its Integrated Resource Plan from one developed in 1997. Recognizing the important role of energy diversity, KIUC developed an aggressive strategic plan for 2008 through 2023. In November, 2007, KIUC committed to generate at least 50% of its electricity using renewable energy by 2023. Currently, KIUC derives the majority of its power from diesel generators and a combustion turbine that uses naphtha (93%). There is also approximately 7% hydro-electric power being generated on the island. The island presently has 5 MW of PV distributed throughout the island, and the new 1 MWAC (1.2 MWDC) Kapa'a Solar PV project brought the total amount to 5 MW. A 1.5 MW utility scale battery storage (1.5 hours) that was installed by Xtreme Power has been operational (operating in frequency regulation mode) since October 2011.

The Hawaii-wide Renewable Portfolio Standards calls for 40% of its electricity to be generated from renewables by 2030. KIUC has planned for utility scale solar PV totaling 30 MW with 12 MW/9 MWH of Battery Energy Storage to come on line within the next 2 years. This includes a PPA for 6 MW of PV located next to KIUC Port Allen facilities and two 12 MW Solar PV farms on the east and south shores of Kauai owned by KIUC subsidiaries. The project is scheduled to be completed by 2014.

System Overview

Utility: KIUC, a non-profit entity with cooperative by-laws, operates two main power plants on Kaua'i: Port Allen and Kapaia Power Station (KPS). Port Allen has 12 generating machines capable of producing 96.5 MW of power. It also has a heat recovery steam generator. The generator uses the waste heat from two of the combustion turbines to produce steam for additional electrical generation. KPS has a 27.5 MW steam-injected gas turbine facility purchased in 2003, and is KIUC's more efficient and cleaner burning plant. This plant provides the majority of the power to the island. Currently KIUC derives 93% of its power from diesel and naphtha. KIUC also maintains the Waiahi hydro power plant, which includes the Upper and Lower Waiahi hydro-electric units, rated at 500 kW and 800 kW respectively. The Waiahi hydro plant, along with several other existing hydros that KIUC purchases power from, provides approximately 7% renewable energy annually.

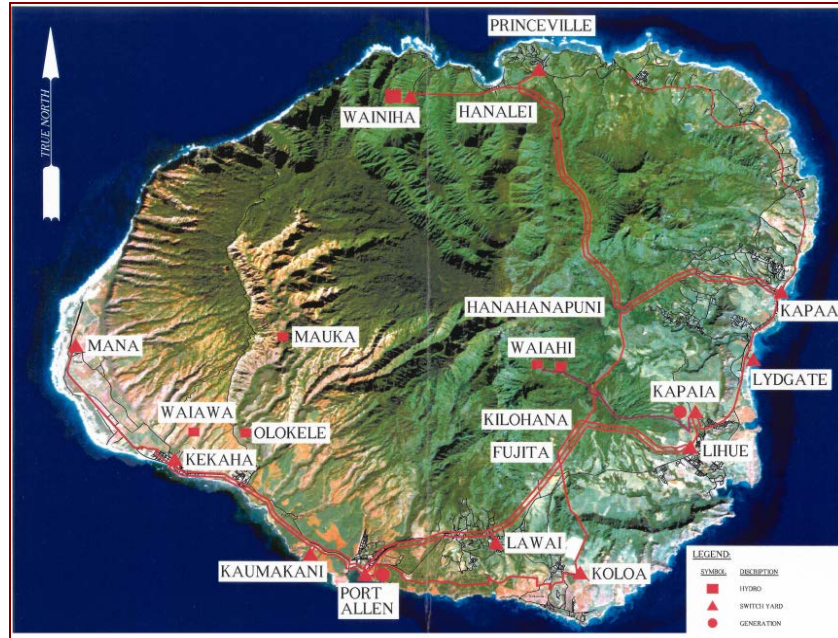


Figure 4-8: KIUC Electrical Generation and Distribution Map (Image courtesy of KIUC)

PV System: Kapa'a Solar LLC is the owner and financier of the PV system, and worked to negotiate a power purchase agreement with KIUC. REC Solar Inc. was the Kapa'a contractor for the installation of the PV system. KIUC, Kapa'a Solar, and REC Solar marked the official completion and commissioning of the 1.2 MW_{DC} solar installation on February 11, 2011. The Kapa'a Solar project is located on Olohena Road, Kapa'a, Hawaii. Figure 4-1 shows an image of the Kapa'a 1.2 MW_{DC} PV system.

Features of the Kapa'a Solar PV system include special corrosion resistance on the racking to protect against exposure, rapid design and build execution, and direct interconnection to the utility's 12.47 kV distribution circuit using a 1000 KVA, 3 phase, 480V/12.8 kV (12.47 kV nominal) transformer. The PV system is ground mounted with 5,376 fixed 225 W PV panels tilted at 21 degrees, and covers an area of approximately 5 acres. There are four 250 kW bipolar inverters by Solaron with an AC operating voltage range of 480 V (432 to 528V), three-phase grounded wye connected. The operating frequency range is 57 to 60.5 Hz. One of KIUC's main concerns with adding more solar to its system is the coordination with the underfrequency load-shedding schemes. UL-listed inverters typically will trip at the IEEE 1547 recommended settings of 59.3 Hz. KIUC would like the inverters to stay on line to coordinate with its load shedding scheme. Thus the Solaron inverter under frequency trip set-point is 57.0 Hz. The inverter under-voltage and over-voltage time delay is set to 2.5 seconds.

Figure 4 3 depicts a simplified single-line diagram of the Kapa'a PV interconnection to KIUC 12.47 kV distribution system.

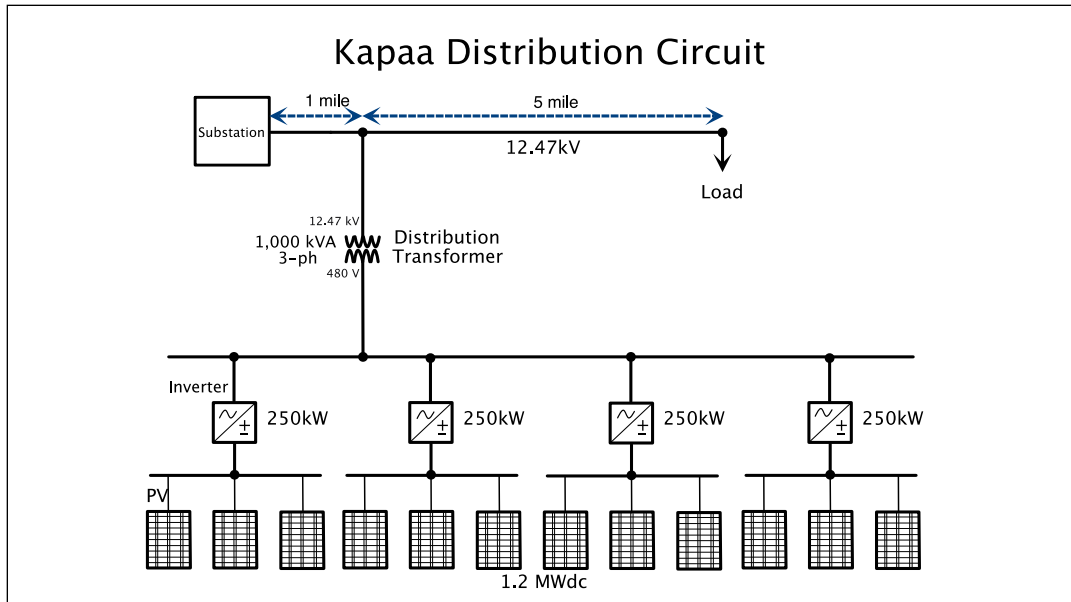


Figure 4-9: Simplified Kapa'a Single-line Diagram

Distribution Network: The mainland power grid uses very high transmission voltages (130 to 765 kV). Islands are smaller and generally transmit electricity at subtransmission levels (25 to 115 kV). The transmission system on Kaua'i is operated at 57.1 kV. Distribution substations around the islands contain transformers that reduce the voltage levels to the distribution voltage level of 12.47 kV. The distribution system was originally designed to deliver power in one direction — from the substation to the customer loads.

Bulk power producers are generally large (greater than 10 MW) and connected at the subtransmission voltage level. Distributed energy resources are sources of electric power that are usually interconnected near the load to the electric power distribution system. They may also include distributed generation with distributed storage.

The PV system is located approximately one mile from KIUC's substation and the total length of the distribution feeder is approximately five miles. The daytime load on this distribution feeder is approximately 1.2 to 1.5 MW peak and night time loads are 2 MW peak. During sunny days, the PV system can supply approximately 90% of the demand required by the distribution circuit to which it is connected. The preliminary results in monitoring this circuit indicate that overall power quality has not been compromised.

Interconnection of the PV System

System Impact Studies: KIUC's power modeling and simulation tools include Uplan, ASPEN Oneliner, Milsoft EA, and PSS/E. Currently, KIUC runs Uplan for its planning activities, PSS/E for powerflow and stability analysis, ASPEN Oneliner for short circuit and protection coordination studies, and Milsoft for Distribution Analysis.

One of KIUC's primary concerns is with the IEEE Std 1547 over-frequency set point of 60.5 Hz. As a small island system with a peak load of 70 MW, when system faults are cleared by the substation circuit breakers under load, frequency regularly exceeds 60.5 Hz. When faults occur during daylight hours, large PV systems as well as the aggregate of smaller residential systems will trip off-line. Both PV customers and KIUC can realize a benefit if the IEEE Std 1547 (60.5 Hz) set point can be increased. PV customers can stay connected through the event while KIUC would benefit from system stability.

Distribution System Upgrades: Presently, there are no known upgrades to the distribution system.

Effects of the PV System

The initial results look very positive. According to KIUC, the monitored results on the distribution feeder on sunny days and cloudy days, with the PV system turned on and the PV system turned off, are showing very little difference in the voltage levels, harmonics, and overall power quality between the different scenarios. These preliminary results suggest that utilities could go to very high levels of PV penetration in localized areas without causing problems for the grid.

Conclusions and Ongoing Studies

Utility Perspectives: KIUC continues to monitor power system events of this distribution feeder with high penetration of PV installed. At times the utility is supplying approximately 90% of a distribution load with PV during the day. To accurately monitor the steady-state and transient response of KIUC PV systems, KIUC has installed data acquisition to capture electrical and environmental data from the installed Kapaa PV system. The data recorded so far has indicated that voltage does vary, however, at the point of interconnection, the voltage remains within the tariff limits of +/- 5 percent of nominal. The data collection will help KIUC meet its goal of 50% of its electricity coming from renewables by 2023.

4 Case Study: 2 MW Plant in Fontana, California

System Highlights

System Owner:	Southern California Edison
Utility:	Southern California Edison
System Integrator:	Southern California Edison
System Size:	2.0 MW _{AC} (prior to Dec. 2010)
Network Type:	Radial
Special Interconnection Requirements:	None



Figure 5-10: View of the 2.0 MW PV System Installed on a Warehouse Rooftop in Fontana, California (Photo courtesy Southern California Edison)

Introduction

The 2.0 MW rooftop-mounted PV system in Fontana, California was the first installed and interconnected system in Southern California Edison's (SCE) Solar Photovoltaic Program (SPVP). This program aims at installing a total of 500 MW of distribution connected PV systems within SCE's territory by 2015.

The PV system and interconnected distribution circuit described in this case study report is being studied under SCE's High-Penetration Photovoltaic Project. A report on the project is available and contains more information about integrating PV systems into the SCE distribution system⁵.

SCE provided the technical information in this chapter.

System Overview

Utility: Southern California Edison is one of the largest investor-owned utilities in the United States. It serves nearly 14 million people in the southern California including most of the greater Los Angeles area.

PV System: The Fontana PV plant denoted as SPVP #1 is located in a warehouse district in the city of Fontana. The system was procured, installed, and interconnected by SCE. The system interconnects to the distribution system using a transformer dedicated to the PV system. The system, although located on industrial warehouse rooftop, is not connected to the transformer serving the warehouse (i.e. the system is not a net energy metering installation).

The installed system includes a total of 30,472 solar modules, 256 DC string combiner boxes, 12 master fuse boxes and four 500 kW inverters⁶. The inverters each connect to 200/480 V transformers that then connect in parallel to a single 480/12 kV transformer that interconnects with the local distribution system.

Distribution Network: The Fontana PV plant is connected to the local 12 kV distribution system about one mile from the local substation. The entire length of the interconnected distribution circuit is 7.8 miles including all mainline and branch circuits. The distribution circuit serves primarily commercial customers as most of the area served by the circuit is a warehouse district. Near the end of the distribution circuit other types of commercial loads, such as retail shops in a mall, are served.

Voltage regulation of the circuit is accomplished by switched capacitor banks placed along the length of the mainline of the distribution circuit. The capacitors are controlled using a time schedule with a voltage override. The voltage override operating set points are adjusted automatically if the ambient temperature, measured at the capacitor bank

⁵ B. Mather, et. al, "Southern California Edison High-Penetration Photovoltaic Project – Year 1," NREL Tech. Report – 5500-50875, 2011.

⁶ G. Rodriguez, "SCE Experience with PV Integration" presented at the EPRI/SEPA/SNL/NREL High Penetration PV Grid Integration Workshop, Tucson, AZ April 19th, 2012.

controller, is above 90° F. Voltage regulation at the substation is also accomplished using switched capacitors located at the substation. The capacitors at the substation are operated to both regulate the voltage at the substation bus bars and compensate VAR flows in the subtransmission system.

A representative one-line diagram of the distribution circuit that interconnects the Fontana PV system is shown in Figure 5-2. The circuit consists of an express overhead run of 653 ACSR (336 ACSR on the neutral) conductors running just past the PV system installation. Then the circuit continues to additional loads via primarily underground cabling. The mainline cabling is mostly 1000 mil JCN but tapers to 750 CLP near the end of the mainline circuit. Overall, with the PV system being nearly the first interconnection to the distribution circuit after it leaves the substation, and the large conductor size, means that the PV system is connected to a relatively stiff (from a voltage standpoint) interconnection.

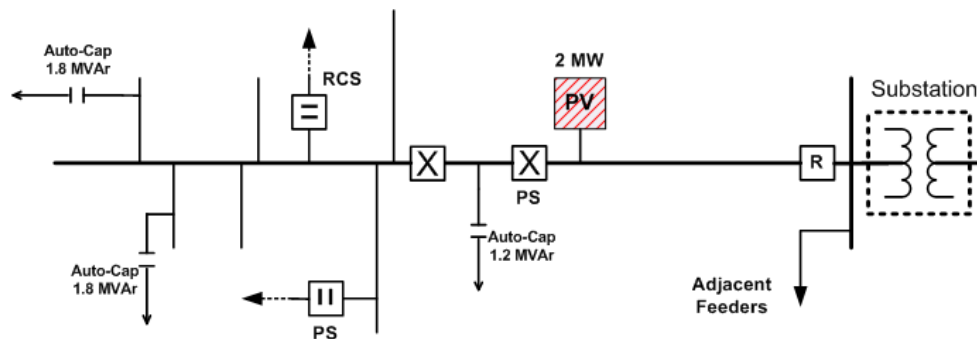


Figure 5-11: Fontana PV System, Substation, and Distribution Circuit

The peak load on the interconnected distribution circuit is approximately 4.2 MW resulting in a PV penetration of about 47%. As the load profile is dominated by commercial loads, specifically warehouses, the circuit loading on days when the warehouses are not operating, such as holidays and weekends, the circuit peak load for the day can be much lower. The peak loading for an off-peak day is estimated to be 2.6 MW, resulting in a PV penetration above 75% for that day.

Interconnection of the PV System

System Impact Studies: SCE’s utility-owned PV systems installed under the SPVP were subject to the same application and study process that non-utility owned PV system installations were subject to. The SPVP systems were mostly, if not all, interconnected under the wholesale distribution access tariff (WDAT) process.

Distribution System Upgrades: No major distribution circuit upgrades were made during the interconnection process of the Fontana PV system. Although unconfirmed, it is likely that the capacitor bank controller settings were modified in order to mitigate some of the effects of variable generation caused by the interconnected PV plant. The capacitor

time delay settings, after capacitor operation, were likely reduced from a standard setting of 2 minutes to 30 seconds.

Effects of the PV System

SCE engineers investigated to see if the PV system resulted in reverse power flow conditions at the substation. Data, collected via the utility SCADA system, was collected and confirmed that no reverse power flow conditions were present at the substation.

Conclusions and Ongoing Studies

Continuing Studies and Research: The circuit mentioned in this case study report was included in the SCE High-Penetration PV Integration Project because a number of other PV systems were likely to be interconnected during the course of the project. This has proven to be true as the aggregate nameplate generation of the interconnected PV plants on the circuit is now 5.5 MW_{AC}. With the additional generation, the impact of the PV generators on the circuit has undoubtedly increased. As part of the SCE High-Penetration PV Integration Project, the circuit has been instrumented with high-speed voltage and current sensing data acquisition devices. This data will be used to quantify the impact of the installed PV systems on the circuit. Based on the impacts found the installed PV inverters will be modified to enable some forms of advanced inverter control (volt/VAR control, curtailment, etc.) in order to reduce the impacts of PV system interconnection on the distribution circuit.