



NREL/SCE High-Penetration PV Integration Project: Report on Field Demonstration of Advanced Inverter Functionality in Fontana, CA

Barry Mather
National Renewable Energy Laboratory

**NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-5D00-62483
August 2014

Contract No. DE-AC36-08GO28308

NREL/SCE High-Penetration PV Integration Project: Report on Field Demonstration of Advanced Inverter Functionality in Fontana, CA

Barry Mather
National Renewable Energy Laboratory

Prepared under Task No. SS12.2910

**NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Available electronically at <http://www.osti.gov/scitech>

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: <mailto:reports@adonis.osti.gov>

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/help/ordermethods.aspx>

Cover Photos: (left to right) photo by Pat Corkery, NREL 16416, photo from SunEdison, NREL 17423, photo by Pat Corkery, NREL 16560, photo by Dennis Schroeder, NREL 17613, photo by Dean Armstrong, NREL 17436, photo by Pat Corkery, NREL 17721.

NREL prints on paper that contains recycled content.

Acknowledgments

This work was supported by the U.S. Department of Energy under Contract No. DOE-EE0002061 with the National Renewable Energy Laboratory and by the California Public Utility Commission (CPUC) through the California Solar Initiative (CSI) Research, Development, and Deployment (RD&D) Program managed by iTron. Additionally, the project would like to thank Southern California Edison (SCE) and its constituent staff for their willing participation in this field demonstration of advanced photovoltaic (PV) inverter functionality to mitigate some of the impacts of high-penetration PV integration.

List of Acronyms

CPR	Clean Power Research
DMU	distribution monitoring unit
EDD	Electrical Distribution Design
NREL	National Renewable Energy Laboratory
PMU	phasor measurement unit
PS	pole switch
PV	photovoltaic
RCS	remote controllable switch
SCADA	supervisory control and data acquisition
SCE	Southern California Edison

Abstract

The National Renewable Energy Laboratory/Southern California Edison High-Penetration PV Integration Project is (1) researching the distribution system level impacts of high-penetration photovoltaic (PV) integration, (2) determining mitigation methods to reduce or eliminate those impacts, and (3) seeking to demonstrate these mitigation methods on actual high-penetration PV distribution circuits. This report describes a field demonstration completed during the fall of 2013 on the Fontana, California, study circuit, which includes a total of 4.5 MW of interconnected utility-scale rooftop PV systems. The demonstration included operating a 2-MW PV system at an off-unity power factor that had been determined during previously completed distribution system modeling and PV impact assessment analyses. Data on the distribution circuit and PV system operations were collected during the 2-week demonstration period. This demonstration reinforces the findings of previous laboratory testing that showed that utility-scale PV inverters are capable of operating at off-unity power factor to mitigate PV impacts; however, because of difficulties setting and retaining PV inverter power factor set points during the field demonstration, it was not possible to demonstrate the effectiveness of off-unity power factor operation to mitigate the voltage impacts of high-penetration PV integration. Lessons learned from this field demonstration are presented to inform future field demonstration efforts.

Table of Contents

1	Introduction.....	1
2	Overview of the Fontana, California, Study Circuit.....	2
3	Overview of Field Demonstration	4
4	Field Demonstration Results and Analysis	5
5	Conclusions and Lessons Learned	13
	References.....	14

List of Figures

Figure 1. Simplified circuit diagram of the Fontana, California, study circuit showing the general connectivity and equipment placement.	3
Figure 2. Real and reactive power flow and the calculated operating power factor of the 2-MW PV system being demonstrated on a clear weather day (September 27, 2013).....	5
Figure 3. Real and reactive power flow and the calculated operating power factor of the 2-MW PV system being demonstrated on a partly cloudy weather day (September 26, 2013).....	7
Figure 4. Real and reactive power flow and the calculated operating power factor of the 2-MW system being demonstrated during the entire demonstration period.....	8
Figure 5. Reactive power flow from the substation to the distribution circuit and the reactive power flow from the 2-MW PV system on September 26, 2013, the second day of the demonstration period.....	10
Figure 6. Real power produced and voltage near the point of common coupling of the PV system (test) on September 26, 2013, the second day of the demonstration period, and the voltage near the point of common coupling during a typical day when the PV system was operating at unity power factor (BL = baseline).....	12

List of Tables

Table 1. Fontana, California, Study Circuit Characteristics	3
---	---

1 Introduction

The field demonstration of the off-unity power factor operation of a photovoltaic (PV) system for the purposes of mitigating the voltage-related PV impacts on the interconnected distribution system is described in the following four sections and had the following objectives:

- Demonstrate the capability of PV inverters to implement advanced reactive power functions
- Demonstrate the effectiveness of these advanced functions to effectively mitigate the voltage-related PV impacts on an actual high-penetration PV distribution circuit.

This field demonstration is part of a project undertaken in 2010 when the National Renewable Energy Laboratory (NREL), Southern California Edison (SCE), Quanta Technology, Satcon Technology Corporation, Electrical Distribution Design (EDD), and Clean Power Research (CPR) teamed together to (1) analyze the impacts of high penetration levels of PV systems interconnected onto the SCE distribution system, (2) develop PV inverter capabilities to mitigate these impacts, and (3) demonstrate the use of these advanced PV inverter functions to mitigate PV impacts in the field. As this project has matured, the capability of PV inverters to implement various advanced functionalities has significantly improved; however, analysis completed on the project in the earlier stages showed that constant off-unity power factor operation would effectively mitigate the bulk of the voltage-related impacts at the distribution system level (Mather et al. 2011). Following the findings of these earlier studies, and taking advantage of the fact that constant power factor operation (also denoted as off-unity power factor operation) was one of the first advanced functionalities/capabilities implemented in many manufacturers' PV inverters, this field demonstration was undertaken to show the capability and effectiveness of constant power factor operation on an actual high-penetration PV distribution circuit.

Section 2 of this report gives a brief description of the Fontana, California, study circuit, which is helpful to understand the results of the field demonstration. A description of the particulars of the field demonstration is reported in Section 3. Section 4 contains the bulk of this report, and it presents the results and analysis arising from the field demonstration. Section 5 concludes the report, and it lists lessons learned from this field demonstration.

2 Overview of the Fontana, California, Study Circuit

The Fontana, California, study circuit is one of three circuits in SCE's territory that has been comprehensively modeled and instrumented to better understand the distribution system level impacts of high-penetration PV integration under the auspices of the NREL/SCE High-Penetration PV Integration Project. In 2010, at the start of the project, the Fontana, California, study circuit had a single 2-MW PV system, which interconnected to the circuit approximately one mile from the substation and had no customers connected between the PV system and the substation (i.e., the first mile of the circuit is considered an "express" section). During the period of the project, the 2-MW PV system was enlarged, resulting in a total nameplate capacity rating of 3 MW for that system. At a later date, a 1.5-MW PV system was installed near the 3-MW PV system, for a total PV capacity rating of 4.5 MW interconnected to the circuit. Figure 1 shows the general configuration of the Fontana, California, study circuit. The PV systems are shown as "2 + 1 MW," denoting the original 2-MW PV system that was enlarged by 1 MW, and "1.5 MW," denoting a nearby but separate system that was installed at a later date.

This medium-voltage (12 kV) circuit serves primarily commercial customers. The primary load on the circuit is a portion of a retail business district located near the end of the circuit. Overhead lines with a flat configuration comprise most of the circuit. The circuit does contain an underground cable section for the main line conductors located on the far half of the circuit as seen from the substation. Table 1 provides some general circuit characteristics.

The circuit's voltage regulation is accomplished solely through the use of switched capacitors. There are no voltage regulators on the circuit, and there is no load tap-changing transformer at the substation. The locations of the four automatically controlled switched capacitor banks are shown in Figure 1. There are also numerous medium-voltage switches, including both remote controllable switch (RCS) and manual pole switch (PS) types. These switches are used for circuit reconfiguration during planned and unplanned outages on this and adjacent circuits.

Data presented in Section 4 of this report was taken from either SCE equipment connected to their distribution supervisory control and data acquisition (SCADA) system (i.e., substation-level data and PV system data) or from a few of the data collection instruments installed on the distribution circuit specifically to quantify the impacts of high-penetration PV integration. These instruments are distribution monitoring units (DMUs). These devices have been developed at NREL and are effectively distribution-level phasor measurement units (PMUs) because they provide 1-second resolution visibility of the circuit's three-phase voltage magnitude and phase angle (referenced to a global positioning system [GPS] disciplined clock) (Bank and Hambrick 2013, Bank and Mather 2013).

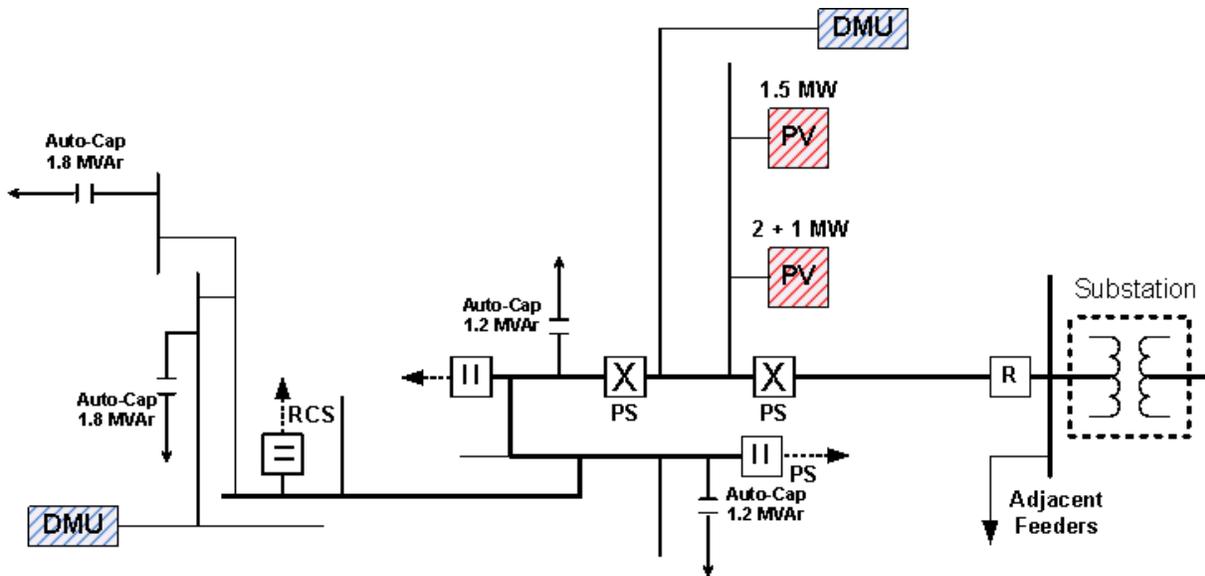


Figure 1. Simplified circuit diagram of the Fontana, California, study circuit showing the general connectivity and equipment placement.

Table 1. Fontana, California, Study Circuit Characteristics

Nominal circuit voltage (primary)	12 kV
Total circuit length (three-phase runs)	7.8 mi
Feeder loading capacity at substation (thermal)	11.9 MVA

3 Overview of Field Demonstration

The field demonstration took place during the 2-week period from September 25, 2013, to October 8, 2013. Scheduling the field demonstration took into account many considerations, such as the expected loading on the distribution circuit during the demonstration period, the likelihood of real power curtailment as a result of the increased apparent power (VA) requirements on PV inverters to operate at off-unity power factor, and SCE's general maintenance schedule and availability for supporting the field demonstration. Previously completed model-based analysis of the Fontana, California, circuit—completed specifically to determine the most effective way to mitigate the impacts of a large PV system interconnected to the circuit using off-unity power factor operation (Mather et al. 2014)—indicated that fall and spring were the seasons when the ratio of PV power generation to distribution circuit load was the highest and thus represented the expected periods of the highest PV-related distribution circuit impacts. This analysis also showed that an operating constant power factor of -0.95 (inductive/absorbing power factor) would effectively counteract the modeled voltage increase along the distribution circuit caused by the real power injection from the large interconnected PV systems.

Additional distribution system modeling was completed to determine the worst-case reactive power flows sourced from equipment located at a substation and/or the general subtransmission system if all reactive power control elements (switched capacitor banks) on the circuit became inoperable and the PV system included in the demonstration continued to operate at the planned inductive power factor. This worst-case reactive power flow was compared to reactive power capability estimates for the interconnected substation, and it was concluded that this unlikely contingency would cause a voltage collapse and/or overload at the local substation and the subtransmission system in general.

Because various models from different manufacturers of PV inverters were used in the two systems in the Fontana, California, study circuit, only 2 MW of the total 4.5 MW of installed PV were available for off-unity power factor operational testing. Four 500-kVA PV inverters that interfaced to the original 2-MW PV system installed in 2009 comprised the study system.

On the morning of September 25, 2013, SCE engineers changed the power factor operating set points on the aforementioned four 500-kVA PV inverters. On the morning of October 8, 2013, the same engineers changed the power factor operating set points back to unity, concluding the field demonstration.

4 Field Demonstration Results and Analysis

Results and analysis from the completed field demonstration are presented below in two subsections that relate to the two primary objectives of the demonstration: demonstration of the capability of PV inverters to implement advanced reactive power functions and the demonstration of these advanced functions to effectively mitigate the voltage-related PV impacts on an actual high-penetration PV distribution circuit.

4.1 Demonstration of PV Inverter Capabilities to Implement Advanced Functionalities (Off-Unity Power Factor Operation)

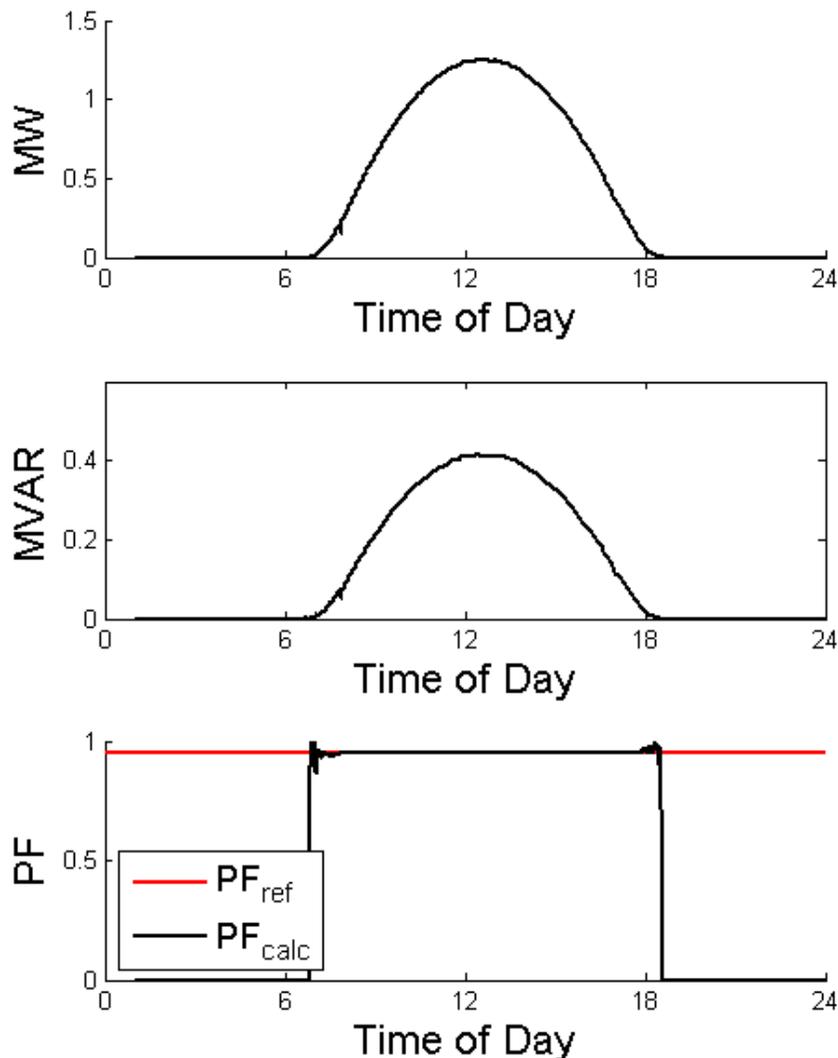


Figure 2. Real and reactive power flow and the calculated operating power factor of the 2-MW PV system being demonstrated on a clear weather day (September 27, 2013).

Figure 2 shows the real (MW) and reactive power (MVAR) flow from the 2-MW PV system included in this field demonstration and the calculated operating power factor of the PV system. The power factor set point (PF_{ref}) is also shown for reference. When the PV system is not generating positive real power, the calculated power factor is undefined. At these points the calculated power factor was set to zero, as shown in Figure 2. At low PV power production levels—because of the limited numerical accuracy of the real and reactive power measurements for low-power operating levels—the calculated power factor is somewhat variable. This variability generates the “Gibbs-ears-like” transitions of the calculated power factor in the morning, when the PV system begins to generate real power, and the evening hours, when real power production tails off.

As shown in Figure 2, the reactive power was being supplied by the PV system. This is contrary to the desired power factor set point determined in earlier modeling studies that suggested that an inductive (absorbing) power factor of -0.95 would mitigate some of the voltage-related impacts on the Fontana, California, circuit. Although there are many conflicting conventions for assigning the direction of reactive power flow, when considering the reactive power flows in the entire distribution circuit (which is shown in the next section), it is clear that the PV system was operating at a capacitive power factor of 0.95 (generating reactive power). Regardless, the power factor set point of the 2-MW PV system that consists of four 500-kW PV inverters was tracked well at the reference set point (albeit an erroneous set point).

Figure 3 presents the same data as those shown in Figure 2, except the weather on the day shown was one of the few variable cloudy days that occurred during the testing period. As shown, the real power (MW) of the PV system ramped up and down during the majority of the daytime, with power swings greater than 1 MW apparent numerous times during the day. Reactive power flow (MVAR) also ramped up and down during the day because the PV system controlled reactive power output to maintain a constant power factor set point. The calculated power factor shows that the PV system being demonstrated tracked the 0.95 power factor set point with considerable accuracy. There were a few periods of time when the calculated power factor diverged from the power factor set point. This plot was developed using 15-s resolution SCADA data from SCE. It is possible that there were short periods of time during large ramping events when the PV system was incapable of accurately tracking the desired PV set point; however, it is more likely that the temporal resolution of the data sensed and reported through the SCADA system may not have been exactly time aligned so that during periods of high variability the sensed real and reactive power measurements during slightly different 15-s intervals could produce similar calculated power factor excursions from the ideally tracked power factor set point.

Regardless, Figure 2 and Figure 3 provide evidence that the PV system being demonstrated is capable of operating at off-unity power factor and that reactive power can be adjusted to regulate the operating power factor to match the power factor set point. Even during periods of high PV system real power variability resulting from partly cloudy weather, the PV system appeared to track the power factor set point with a high accuracy and it is likely that excursions from the set point power factor were caused by the use of slightly non-synchronized real and reactive power measurements.

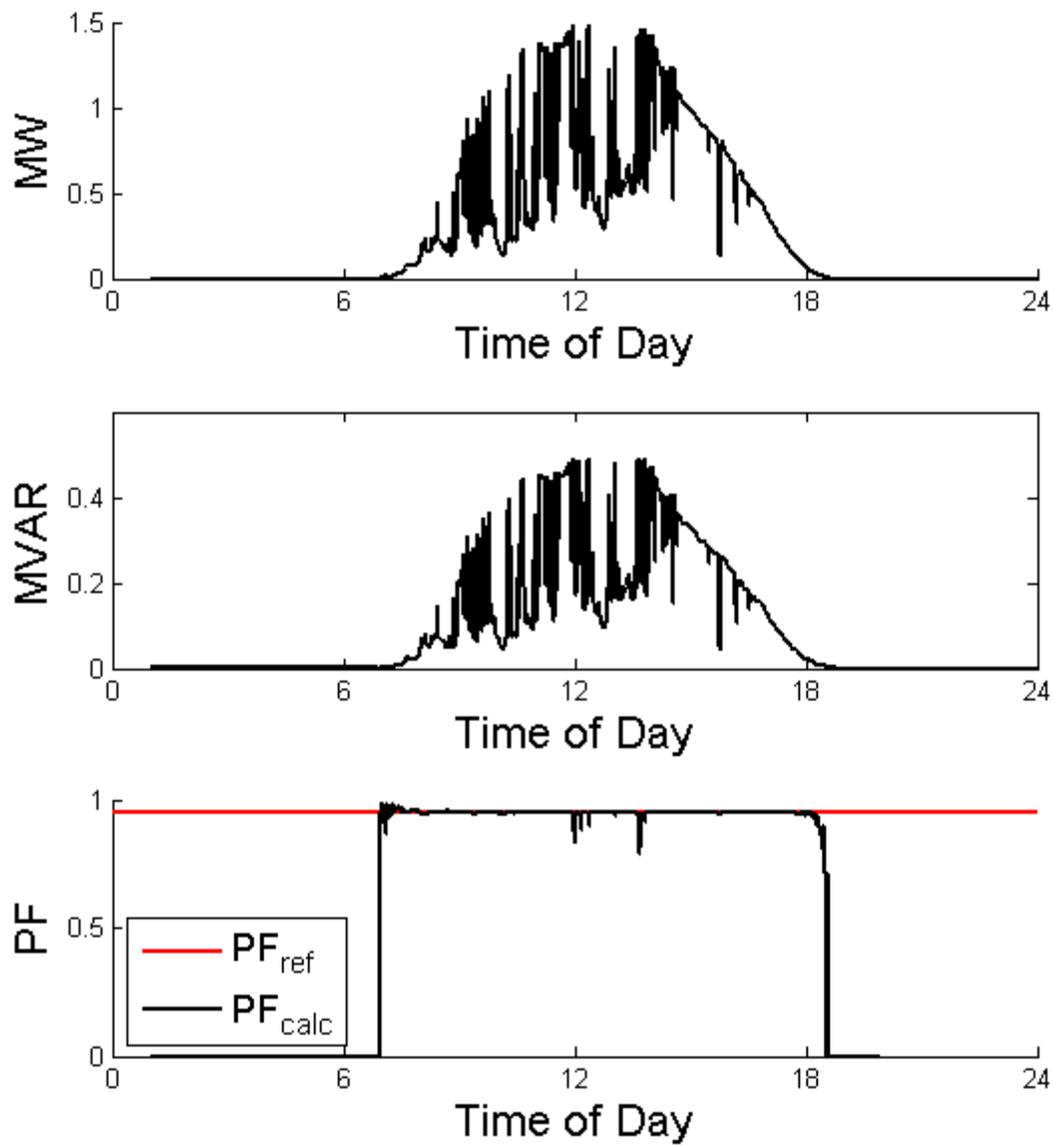


Figure 3. Real and reactive power flow and the calculated operating power factor of the 2-MW PV system being demonstrated on a partly cloudy weather day (September 26, 2013).

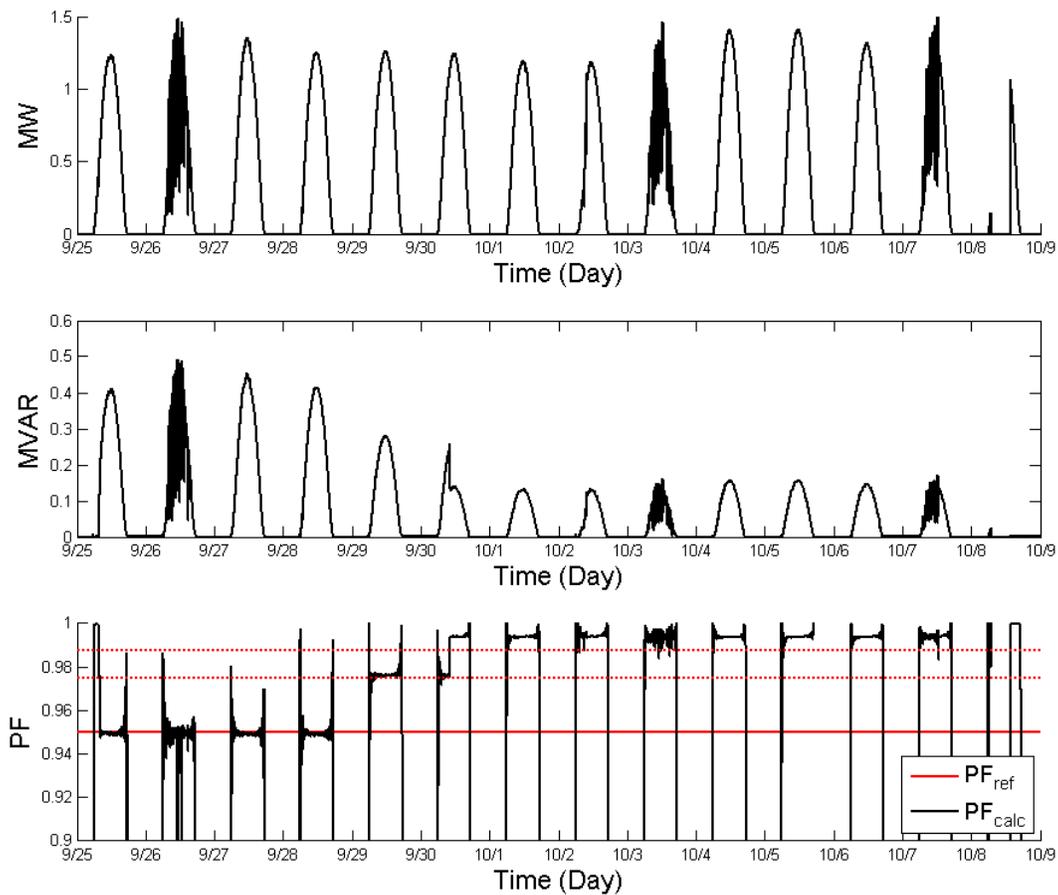


Figure 4. Real and reactive power flow and the calculated operating power factor of the 2-MW system being demonstrated during the entire demonstration period.

Post-processing of the field demonstration data determined that the effective power factor set point (or the individual power factor set points of the four 400-kW PV inverters that comprise the PV system) was not constant during the testing period. SCE engineers and field crew implemented the power factor set points at the beginning of the field demonstration period and did not modify the power factor set points until the end of the field demonstration period; thus, any changes during the field demonstration were the result of the operation of the PV system and its constituent components. As shown in Figure 4, which presents the real and reactive power supplied by the 2-MW PV system as well as the calculated power factor, the power factor set point of 0.95 was implemented for approximately the first 4 days of the demonstration period.

On the fifth day (or during the preceding evening), two of the 500-kW PV inverters apparently reverted to unity power factor operation, which resulted in an overall PV system operating power factor of 0.975. This set point was accurately tracked for slightly more than 1 day, at which point it appears that another 500-kW PV inverter reverted to unity power factor operation. For the rest of the demonstration period, the PV system operating power factor was greater than 0.9875, which would be the expected overall PV system operating power factor if all PV inverters had

the same real power output, three PV inverters were operating at unity power factor, and one PV inverter was operating at the demonstration power factor set point of 0.95.

Figure 4 shows that the field demonstration ended on October, 8, 2013, and that no reactive power output resulted even though the system began to generate real power in the afternoon.

It is likely that the PV inverters reverted to operating at unity power factor because the power factor set point was implemented at the beginning of the field demonstration period. The power factor on all four PV inverters was set via the user-interface panel. Clearly, the PV inverters operated after the power factor set point had been entered via the user-interface panel, but it is speculated that as the PV inverters effectively reset (either by a hard reset or software reset), they reverted to a unity power factor set point that is stored in nonvolatile memory.

4.2 Demonstration of Off-Unity Power Factor Operation to Mitigate the Distribution System Level Impacts of High-Penetration PV Integration

This section describes the data analysis completed to attempt to determine the effectiveness of mitigating voltage-related PV system impacts via off-unity power factor operation during the field demonstration. As mentioned in the preceding section, the implemented power factor set point realized during the field demonstration was not the proposed power factor set point determined for optimal studies of PV-impact mitigation. This error limited the usefulness of the overall demonstration, but a few important insights were determined.

At the beginning of the field demonstration, near-real-time SCADA-level data from SCE were queried to verify the operation of the PV system being demonstrated. As shown in Figure 2 and Figure 3, the PV system did operate at a power factor set point of 0.95, but there was some uncertainty as to the direction of the reactive power flow. There are many conventions for reactive power flow, and these conventions are a result of the viewpoints and objectives of the engineers who use them. For instance, transmission engineers typically denote positive reactive power flow as capacitive (i.e., capacitors generate vars). For distributed energy resources such as PV systems, there is often additional confusion surrounding real and reactive power flow because these resources typically generate real power instead of consuming real power, like typical loads on the distribution circuit; thus, metering is often set up with reversed-current transformers so that real power delivered to the grid is measured as positive. Regardless, the sign error (supplying instead of absorbing vars) occurred in the initiation of this field demonstration. It is important to note that this error was not caused by the SCE engineers and line crew who implemented the power factor set points on the PV system; rather, it was caused by not clearly communicating the expected power factor set point for the field demonstration and by not verifying the reactive power measurement sign convention before or during the demonstration.

To verify the implemented power factor set point, the reactive power flow supplied from the substation/subtransmission system was investigated. Figure 5 shows the reactive power flow at the start of the circuit from the substation (upper left) and the reactive power flow (shown as positive) from the PV system during variable weather conditions during the demonstration period. Voltage regulation along the distribution circuit was accomplished using switched capacitors that for this analysis were considered suppliers of positive vars (var generators). As

shown in Figure 5, one capacitor switched on at approximately 5:00 a.m. and another capacitor switched on at approximately 7:00 a.m. Bringing these var generators online greatly reduced the amount of capacitive vars sourced from the substation/subtransmission system. The red lines shown on the reactive power flow from the substation ($MVAR_{sub}$) plot indicate a var reduction of 1.2 MVAR, which is equivalent to a rating of one of the capacitor banks on the Fontana, California, study circuit (see Figure 1). The preceding analysis verified that the convention of the substation reactive power flow is that inductive reactive power flow is positive and capacitive reactive power flow is negative.

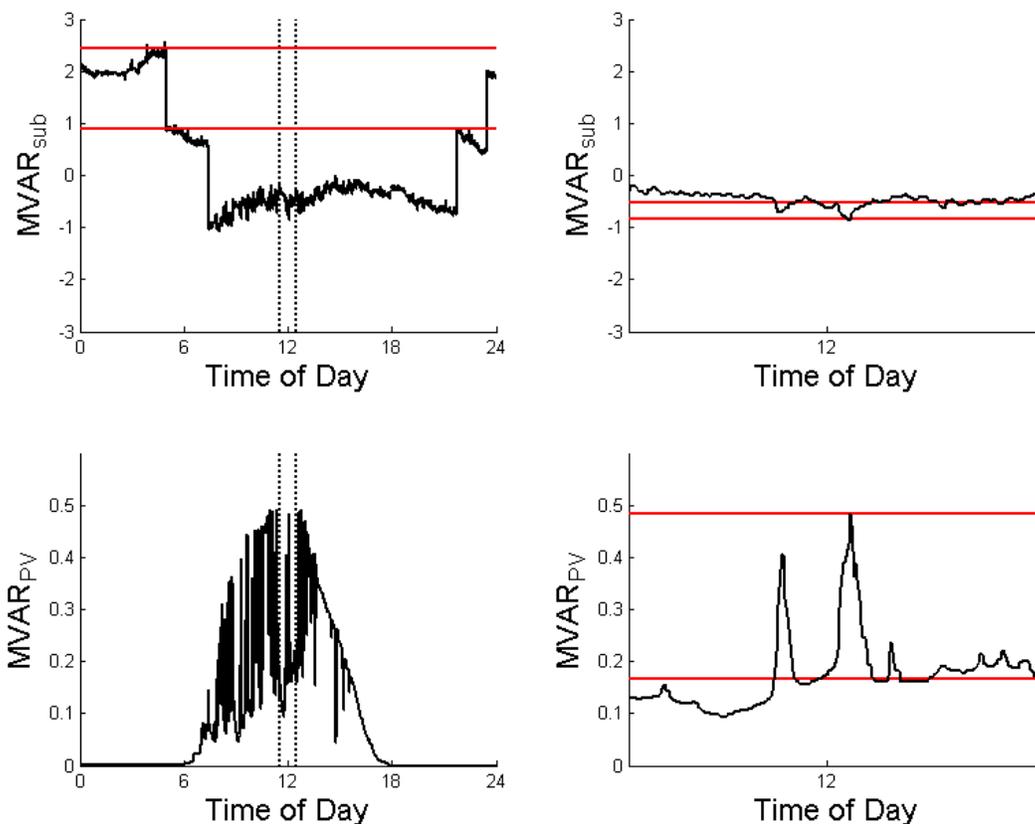


Figure 5. Reactive power flow from the substation to the distribution circuit and the reactive power flow from the 2-MW PV system on September 26, 2013, the second day of the demonstration period.

Focusing on a time range of 15 minutes before and after noon, the plots on the right in Figure 5 show the impacts of the reactive power flow developed by the PV system being demonstrated, and its reactive sign convention can be determined. The two large reactive power spikes shown during this time period occurred as a result of the highly variable operation of the real power of the PV system due to partly cloudy weather conditions. The magnitude of the largest spike—as delineated by red construction lines—was approximately 0.32 MVAR. A reactive power change of the same magnitude is also shown via construction lines in the reactive power flow from the distribution circuit’s substation ($MVAR_{sub}$). The two reactive power spikes were mirrored in the

substation reactive power flow, clearly indicating that the PV system was operating at a capacitive (supplying) power factor.

The ramifications of operating at a capacitive power factor instead of an inductive power factor are that voltage variations on the distribution circuit caused by the PV system should be exacerbated. As the real power of the PV system increases, the voltage at the point of interconnection should rise even higher than if the PV system operated at a unity power factor. Because the intended mitigating power factor set point of -0.95 (inductive) very nearly eliminated the voltage variation impact on the distribution circuit, the actual operating power factor of +0.95 capacitive should have nearly doubled the voltage variation impact at the point of interconnection.

Unfortunately, as shown in Figure 6, the effectiveness of mitigating PV impacts on voltage-related distribution circuit impacts, or rather the exacerbation of these impacts as a result of accidentally set power factor operating points, is not clearly reflected in the voltage data collected during the demonstration period. Figure 6 shows the real power produced by the 2-MW PV system during a partly cloudy day. The system was operating at a power factor of +0.95 capacitive. The voltage at the point of common coupling is shown for the same period ($V_{PCC,test}$) and a day with similar circuit loading, but with the PV system operating at unity power factor ($V_{PCC,BL}$). Plots on the left of the figure show variations throughout the entire day, and plots on the right of the figure show variations during a 30-minute period centered on noon. As shown, the variations in real power production, which caused variations in the reactive power supplied to the circuit, did not clearly change the voltage on the circuit at the closest voltage sensor on the instrumented distribution circuit. In fact, when comparing the $V_{PCC,test}$ to $V_{PCC,BL}$ plots, it is difficult to see any real difference in the system voltage and its character at that point because of the operation of the PV system nearby. It should be noted that the voltage sensor (as shown in Figure 1) is not located directly at the PV system point of common coupling but is on a nearby short lateral. Sensing at the exact point of common coupling was not possible because of tariff regulations and the availability of three-phase pad-mount transformers near the PV system.

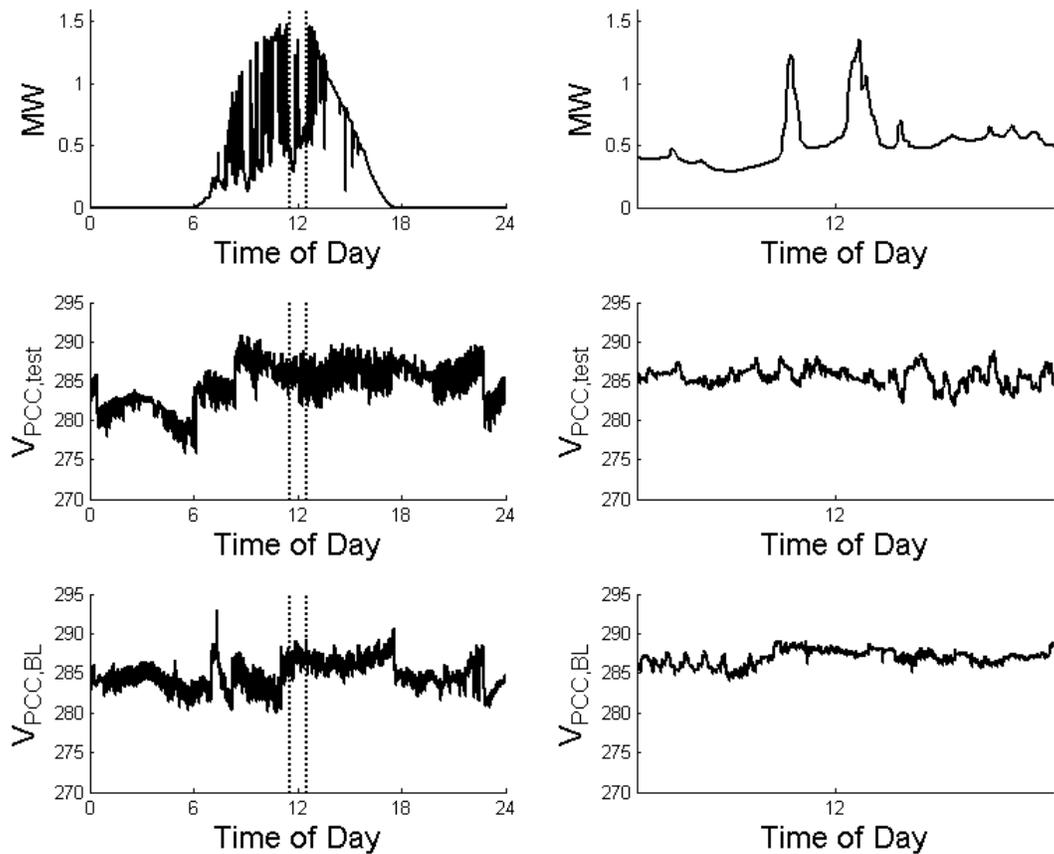


Figure 6. Real power produced and voltage near the point of common coupling of the PV system (test) on September 26, 2013, the second day of the demonstration period, and the voltage near the point of common coupling during a typical day when the PV system was operating at unity power factor (BL = baseline).

5 Conclusions and Lessons Learned

Although the field demonstration did not go as originally planned because the PV system operated at a capacitive power factor set point of +0.95 instead of the expected induction power factor set point of -0.95, there were a few conclusions and lessons learned that are applicable to additional field demonstrations in the future. The field demonstration did reinforce previous laboratory experiments that showed that utility-scale PV inverters are capable of implementing off-unity power factor operation with relatively high bandwidth (Mather, Kromer, and Casey 2013; Langston et al. 2012). The data collected show that the PV system was able to implement off-unity power factor operation, meeting the first objective of the field demonstration.

The second objective, which was to show the effectiveness of off-unity power factor operation to mitigate the voltage-related impacts of high-penetration PV integration on the Fontana, California, study circuit, was not met by this field demonstration. However, a number of lessons were learned that will make future field demonstrations, planned for completion on the Fontana, California, study circuit and one additional SCE study circuit in late 2014, more successful. These lessons are:

- Utility engineers and line crews that interface with the PV systems to implement off-unity power factor set points need to be better informed with regarding the specific set points requested. Capacitive reactive power use is very well understood within the utility sector, but the use of inductive reactive power is not. In fact, it is counterintuitive to many utility engineers and line crew members to operate any utility-controlled device in a manner that absorbs reactive power. Through better communication, the correct power factor set points can be assured in future field demonstrations.
- To ensure that power factor set points are maintained during the entirety of the field demonstration, the power factor set points need to be set in the nonvolatile memory of the PV inverters so that they do not revert to the off-unity power factor set points during hard or soft restarts.
- Voltage sensing for the purposes of measuring the effectiveness of PV mitigation needs to be connected as close as possible to the actual point of common coupling of the PV system. When sensing the system voltage on the secondary side of a transformer, transformer loading has proven to be too insensitive (even when accounting for transformer loading). A primary voltage-sensing solution may be the only way to accurately measure these voltage changes on circuits like those in the Fontana, California, study circuit that have relatively little impedance between the substation and the point of common coupling of the PV system.

References

Bank, J.; Hambrick, J. (2013). *Development of a High-Resolution Real-Time Distribution-Level Metering System and Associated Visualization, Modeling, and Data Analysis Functions*. NREL/TP-5500-56610. Golden, CO: National Renewable Energy Laboratory, May. Accessed July 29, 2014: <http://www.nrel.gov/docs/fy13osti/56610.pdf>.

Bank, J.; Mather, B. (2013). “Analysis of the Impacts of Distribution-Connected PV Using High-Speed Data Sets.” IEEE Green Technologies Conference Proceedings; April 4–5, Denver, Colorado.

Langston, J. et al. (2012). “Power Hardware-in-the-Loop Testing of a 500-kW Photovoltaic Array Inverter.” IEEE Industrial Electronics Society Conferences Proceedings; Oct. 25–28; Montreal, Quebec.

Mather, B., et al. (2011). *Southern California Edison High-Penetration Photovoltaic Project—Year 1*. NREL/TP-5500-50875. Golden, CO: National Renewable Energy Laboratory, June. Accessed July 29, 2014: <http://www.nrel.gov/docs/fy11osti/50875.pdf>.

Mather, B., et al. (2014). *NREL/SCE High Penetration PV Integration Project: FY13 Annual Report*. NREL/TP-5D00-61269. Golden, CO: National Renewable Energy Laboratory, June. Accessed July 29, 2014: <http://www.nrel.gov/docs/fy14osti/61269.pdf>.

Mather, B.; Kromer, M.; Casey, L. (2013). “Advanced Photovoltaic Inverter Functionality Using 500-kW Power Hardware-in-Loop Complete System Laboratory Testing.” IEEE Smart Grid Technologies Conference Proceedings; Feb. 24–27, Washington, D.C.