Field Verification and Data Analysis of High PV Penetration Impacts on Distribution Systems

Farid Katiraei*, Barry Mather**, Ahmadreza Momeni*, Li Yu*, and Gerardo Sanchez*

* Quanta Technology, Raleigh, NC 27607, USA
** National Renewable Energy Laboratory (NREL), Golden, CO 80401, USA

Abstract — This paper describes a methodology for field evaluation of large PV system impacts on distribution systems based on data collected from several phasor measurement devices deployed on two distribution feeders. The method utilizes a series of performance indicators and pattern trending approaches to process large amounts of granular data gathered from fielded data acquisition instruments (1 second GPS time-synchronized phasor measurements). A summary of key observations and findings from data analysis approach and field verified effects are provided in the paper to explain key operational concerns and future design challenges. The approach mainly focuses on analysis of voltage and current profiles of distribution feeders at primary feeder level (e.g. 12 kV) for various daily and seasonal conditions to identify and evaluate events with adverse power quality impacts. Event categories are proposed and used to classify types of events based on the level of severity in the range or rate of voltage or frequency variations. The proposed approach was proven to be very effective to investigate field issues and to capture events.

Index Terms — power distribution systems, PV integration impact study, power quality in feeders, analysis of field data.

I. INTRODUCTION

As part of the high penetration PV projects funded by Department of Energy (DOE) SunShot Program, three distribution feeders with large utility-scale PV systems were selected to deploy voltage and current measurement devices at several locations on the feeders [1]. Two types of measurement devices were deployed on the feeders for granular voltage and current phasor measurements at 1 and 5 second intervals respectively over a period of several months. Data measurements from each set of data acquisition instruments were communicated to a centralized location via the cellular communications network and collected in a database server for off-line analysis.

Data analyses were extensively performed for two distribution circuits, based on availability and quality of the data (For some other related studies from the authors, see [2] and [3]). The data set utilized for this study included voltages and currents gathered in a period of approximately 17 months from April 2013 to September 2014. The analyzed circuits are named Feeder 1 and Feeder 2 in this paper for simplicity.

Feeder 1 is a 12.47 kV rural feeder supplied from a 66 kV substation. This feeder supplies mostly agricultural lands and farm area. There are two switched capacitor banks on the feeder which are operating with time-biased and voltage override. A 5 MW ground mounted PV plant is interconnected to this feeder toward the end of the feeder. During light load condition of the feeder, reverse power flow can be observed at feeder head.

Feeder 2 is a 12.47 kV rural feeder supplied from a 66 kV substation. Two 1.5 MW ground mounted PV plants are interconnected to this feeder on the middle of one of the main branches. Feeder is very lightly loaded, causing significant reverse power flow toward the substation. There are no voltage control devices on this feeder.

II. DATA ANALYSIS METHODOLOGY

To visualize the impact of PV plants and to detect potential issues, several power quality indicators are suggested. The indicators deal with duration and severity of voltage deviations as well as the extent of power flow and reactive power variations in the circuit. Examples of the indicators are defined below.

"Rapid voltage variation" is defined as the maximum voltage variations in periods of one hour or less. This indicator is of interest to quantify the level of voltage disturbances introduced either by normal changes in load, or by the cumulative action of load changes and PV output variations for cloud movement.

Slow voltage variations “∆V due to PV Generation” is another indicator that was used to determine the average difference in voltage between the cases when the PV plant output is not generating power, to moments of maximum PV generation. Similarly, the maximum and the minimum voltages registered through specific days were recorded as indicators of interest.

Other indicators that were monitored in this study are the maximum current supplied by the PV plant in a given season, the maximum power output incursions due to cloud movements, the daylight span for specific seasons, and the duration of reverse power flow at the respective substation.

Analysis of measurements was done for several specific days that let see the most important effects of meteorological conditions on the PV plant, and on the rest of the circuit where
the solar PV plant is connected. The days analyzed were selected according to extremes in the amount of solar irradiation, cloud patterns, and load characteristics. This lead to consider days in summer and winter seasons, with high and low load conditions, and characterized by their respective cloud patterns that are linked to variations in solar irradiance.

III. FIELD DATA ANALYSIS RESULTS AND OBSERVATIONS FOR PV IMPACT STUDY

In this section, a detailed discussion on the observations and examples of event captures for both Feeders 1 and 2 on February 1, 2014, are described. These two days are a sample of the days on which the impact of the reverse power flow on the feeder voltage is significant, and there are important power quality concerns

Case Study I: Feeder 1, on February 1, 2014

February 1, 2014 had a sunlight span of approximately 10 hours, negligible cloud variations, and moderate solar intensity, as shown in Figure 1. PV output variations due to cloud movement were negligible. As seen in this figure, the maximum current provided by the PV branch was 150A, where an approximate load between 3A and 6A was being supplied in the same branch.

The amount of PV generation caused a reverse power flow at the substation that lasted 8.1 hours as can be seen in Figures 2 and 3.

The largest voltage sensitivity on PV generation is roughly about 3% (Figure 4). This happens in a location close to the PV plant, where the short circuit capacity is 24 MVA. The smallest dependency on PV variations occurs at the substation, where the voltage variation is roughly about 1.8% in average (Figure 5), and the short circuit capacity is 191 MVA.

Disregarding some voltage variations attributed to night and early morning load behavior that is not observed during the rest of the day, rapid voltage variation caused by normal load variations is observed to be below 0.7% in a location close to the PV plant (Figure 4), and below 0.7% at the substation (Figure 5).
When cloud movement is considered, the rapid voltage variation is below 1% in a location close to the PV plant (Figure 4), and below 1% at the substation (Figure 5). Additionally, variations shown in Figures 4 and 5 do not imply capacitor operations; voltage at the PV plant, close to a capacitor bank, surpasses the 1.05 pu level from approximately 9:30 to 15:30, at times when the PV output is high. However no capacitor operation is observed. Through the rest of the day, voltage remains within the ±5% limits. It is noted that this 5% permissible voltage level is chosen according to IEEE 1547.a standard [4].

**Case Study II: Feeder 2, on February 1, 2014**

February 1, 2014 had a sunlight span of approximately 9.5 hours with almost no variations in solar irradiance caused by cloud movement, as shown in Figure 6. As seen in this figure, the maximum current provided by the PV branch was 133A, where there was no load supplied to the PV branch.

The amount of PV generation caused reverse power flow for about 9.5 hours at the substation as can be seen in Figures 7 and 8.

The voltage sensitivity on PV generation is roughly about 3% in allocation close to the PV plant (Figure 9). At the end of the main branch on Feeder 2, when high load operations are disregarded, the approximate voltage variation due to PV output is 1.8%, where the short circuit capacity is 35 MVA. This is shown in Figure 10, where the voltage variations are attributed to high load switching operations. At the end of the lateral branch on Feeder 2, voltage dependency on PV variations is about 1.5% in average (Figure 11), and the short circuit capacity is 22 MVA.

**Fig. 6.** Current profile close to the PV plant on Feeder 2 (Date: February 1, 2014).

**Fig. 7.** Current profile at the substation of Feeder 2 (Date: February 1, 2014).

**Fig. 8.** Duration of reverse power flow at the substation of Feeder 2 (Date: February 1, 2014).

**Fig. 9.** Voltage profile close to PV plant on Feeder 2 (Date: February 1, 2014).

**Fig. 10.** Voltage profile at the end of the main branch on Feeder 2 (Date: February 1, 2014).

From the analysis of the voltage profile in Figure 12, it can be observed that the PV system utilizes power factor adjustment or power curtailment to reduce the voltage, once
the voltage at Point 1 (PV system point of interconnection) is above 1.05 pu. It seems that the control approach has some delay in sensing voltage and determination of power factor or curtailment level. It could be also that control was only applied once the voltage exceeded 1.06 pu, and terminated when voltage fell below 1.045 pu. The control scheme has been selected such that the voltage at the PV system point of interconnection (POI) can be limited to about 1.05 pu.

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III. CONCLUSIONS ON THIS PV IMPACT STUDY

A summary of the major observations concluded for the two feeders in this study, based on the analysis of the voltage and current data collected from the field is given below:

- The short circuit capacity (SCC) at different points of the circuit, demonstrated to be a good indicator of voltage robustness, where locations with higher SCCs were showing less voltage deviations due to PV generation intermittency, and lower SCCs corresponded to points in the circuit more susceptible to large voltage fluctuations.
- The maximum PV generation in Feeder 1 was decreased from 100% in summer to 68% in winter. In Feeder 2, the maximum generation was the same for both seasons.
- In cloudy and windy days, highly variable cloud patterns typically caused PV fluctuations with up to 70% depth of changes in the power output.
- Reverse power flow occurred consistently in both feeders. At the feeder head for feeder 1, the reverse power flow can last for up to 8.1 hours approximately. In the case of feeder 2, the reverse power flow can last for up to 10.9 hours approximately.
- In case of feeder 1, there were occasional and infrequent overvoltage conditions (voltages greater than 1.05pu), however, no capacitor operation that could be associated with the PV plant output fluctuations was detected.
- In case of feeder 2, voltage surpassed the 1.05 pu limit typically at all times when PV generation was relatively high (above 60-70% of rated capacity). Operation with leading power factor at all time, as well as PV power curtailment under extreme voltage conditions were observed to be used as a measure to limit large overvoltage to about 1.06 pu. Feeder 2 does not have capacitors installed.
- Average voltage deviations (throughout the day) in feeder 1 are typically in 4% range for the area closer to the PV plant. In case of feeder 2, average voltage variations are typically in 3% range. To put into perspective, it should be noted that SCC close to the PV site in feeder 1 is about 27 MVA, while the corresponding SCC for feeder 2 is about 62 MVA. In addition, feeder 1 has a 5 MW PV system operating time of the day. In the case of feeder 2, both PV curtailment and operation at a very low leading power factor of 0.85 have to be applied to keep the voltage close to 1.05 pu. This has added extensive reactive power flow to the feeder, causing additional loses.

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closed to unity power factor, where feeder 2 PV system is 3 MW in size and most of the time is operated with a low leading power factor (absorbing reactive power), and at reduced output (power curtailment) under extreme voltage conditions.

- Rapid voltage variations occurring in periods less than one hour, and caused by PV intermittency, are in the range of 3.5% for both feeders. Sudden voltage changes in feeder 2 could be much higher, but they are managed by operating at off-unity leading power factor.

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