CHARACTERIZING SOLAR PV OUTPUT VARIABILITY AND EFFECTS ON THE ELECTRIC SYSTEM IN FLORIDA, INITIAL RESULTS

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ABSTRACT

This paper shares initial results from a major collaborative project in Florida underway to study and address effects of high penetration levels of solar photovoltaic (PV) generation on the electric power system. The effort includes characterizing the variability of the solar resource in Florida, where a number of new multi-megawatt solar projects have either recently come online or are in the planning or construction stages (including the largest solar PV generating station in N. America at the time of this writing). Until now, most work on characterizing solar variability has focused on the Southwestern U.S. This paper shares initial results and insights on the variability of Solar PV generation output in Florida on different timescales and provides some preliminary insights into the implications and effects of the variability on the successful integration of increasingly higher penetration levels of solar PV, with respect to the integration technology, control systems, and the electric power system.

INTRODUCTION

The movement towards renewable energy sources as a means to meet the energy needs of the human population with reduced use of fossil fuels, reduced total air emissions and environmental impact, and reduced dependence on non-domestic fuels sources had driven steady growth in deployment of grid-connected solar photovoltaic (PV) energy sources across the globe. This is expected to continue as policy and incentives help offset solar PV at current levelized cost of electricity (LCOE) levels and as research and development and federal investments focused on reducing cost, such as the U.S. Department of Energy’s Sunshot program, drive costs down further towards “grid parity”, where the cost of new solar PV becomes equivalent to the average cost of grid power, currently supplied mostly from fossil, nuclear, and hydroelectric energy sources.

The electric power grid is designed for two-way flow of power at the transmission level and, for the most part, one-way, radially-distributed power, at the distribution level. Further, because electric energy must be delivered reliably in real-time, the current electric system relies heavily on dispatchable electric generation that is available when needed. Distributed generation, such as solar PV, when connected on the distribution system, can redistribute energy flow on distribution feeder in a way that affects voltage regulation, protection devices, safety in maintenance and restoration, and operating procedures. These challenges are compounded when energy is derived from intermittent resources such as solar and wind.

Studying the effects of high levels of grid-connected solar PV on the electric system, then, necessitates an understanding of the variability of the resource. This is an active area of investigation across the solar energy stakeholder community. In the U.S., most efforts to collect and analyze solar resource data and study variability have focused on the Western U.S. This paper discusses initial results of an initiative focused on the Southeastern U.S., particularly Florida.
APPROACH

Data are being collected and examined from geographically dispersed collection sites across the state of Florida. Data are collected with different sampling rates, with sample periods ranging from 250 ms to 15 min. While most prior work has focused on solar irradiance data, such as Global Horizontal Irradiance (GHI) [1], this work focuses primarily on PV system AC output variation, because, that is the variation the electric grid sees. In particular, we are interested in voltage, current, frequency, and real and reactive power at the output of the solar PV inverter. We will also be examining the PV system itself, with a focus on how the resource intermittency (irradiance and the DC power output from the PV panels) passes through to the grid and the important factors within the conversion process with respect to that.

The effect of solar PV variation passing into the electric system will depend upon the respective process dynamics and protection and control response times on the electric grid side. These vary from milliseconds, in the case of certain function of protective relaying and local generator-excitee controls, to minutes, in the case of boilers, grid stability, and load-shedding, to hours and days, in the case of generation scheduling (i.e. unit commitment) [2]. For example, current standards for distributed generation (DG) connected on the distribution system call for DG to disconnect or “cease to energize” the distribution system within between 160 ms and 2 s from detection of abnormal voltage [3]. Therefore, with respect to how solar PV intermittency will affect the power system, the ramp rates and the periodicity of the data are of particular interest. In addition to examining the time-series data itself, this leads us also to the use of power spectrum as a good starting point for analysis, in that it requires less preprocessing of the PV output data to reveal some of the important characteristics of interest than possibly other more direct, conventional statistical comparison metrics.

DATA

While a wide variety of sites and sample rates will be analyzed as the initiative progresses, the initial work described here focuses primarily on data from two locations, one in Lakeland, FL, the other in St. Petersburg, FL. Both are centrally located in latitude with respect to the Florida peninsula, with the Lakeland location being inland, and, the St. Petersburg location being on the West coast. Data are examined at 3 s sample rates for the St. Petersburg site and a 1 min. sample rate for the Lakeland site. In both cases, AC power output from the solar PV inverter is examined, with minimal preprocessing. Periods are selected where the consistency and quality of the data appear acceptable and the data sets for the periods of sunshine are complete (i.e. no missing data during daytime hours).

RESULTS AND ANALYSIS

Using 1 min. data, AC power output from a solar PV system located in Lakeland, FL, having a rated capacity of 250 kWAC, is examined and compared for three days in July 2010 and three days in December 2010. Figure 1 shows AC power output for three days in July, where, a great deal of variability is evident, attributable to typical summer weather patterns in the FL peninsula, consisting of storms that form and dissipate quickly, with the most rapid changes typically occurring in the afternoon. Very steep ramp rates are observed after noon on 7/2 and 7/3, the steepest 1-min ramp rates being 109 kW/min. on 7/2, and 146 kW/min. on 7/3. 5-min. ramp rate maximums are 32 kW/min. on both 7/2 and 7/3. Figure 2, showing data from the Florida Automated Weather Network (FAWN), confirms significant rainfall activity on these days.

Figure 1. Lakeland Center 250 kW solar PV system AC power output, July 2010

Figure 2. Lakeland area weather, July 2010
Figure 3 shows AC power output for the same system for three days in December 2010. There is significantly less variability evident in the time-series data, due to the absence of rainfall and accompanying storms, as confirmed by FAWN data shown in Figure 4. Some variability, small compared to the same days in July, can be seen around peak production times each day, and, the peak production is observed to vary by about 5-10% day-to-day.

As a first step towards characterizing and understanding the nature of the variation, a power spectrum was performed on the July 2010 1-minute PV system AC output data. Figure 5 shows a plot of these results for cycles up to 2000 min. in period. This reveals the expected 24-hour cycle, providing some basic degree of confidence in the discrete Fourier transform (DFT) algorithm used to generate the power spectrum. Reducing the horizontal scale to reveal cycles with intraday periods produces the power spectrum shown in Figure 6. The appearance of strong peaks with periods of 3 hr to 12 hr is consistent with prior work by Curtright and Apt [4] and Lave and Kleissl [1], looking at cyclical nature of solar irradiance for sites in Arizona and Colorado, respectively. Data from these prior works and this show a similar strong reduction of high-frequency variability at periods below approximately 3 hours. It cannot be assumed that time-series data on solar irradiance or solar PV system AC power output fit a stationary stochastic model [5]. The straightforward power spectrum approach alone may not provide sufficient understanding of the nature of the variability.

To take a look at what higher resolution data could reveal about intermittency and the impact on grid-connected PV, data were collected from two sites in St. Petersburg, FL, within close proximity (around 985 yards) and another site (Lowry Park zoo) ~35 miles farther, in Tampa, FL. The plot of the raw data, as shown in Figure 7 and Figure 8, indicates a strong correlation between their outputs. The data was collected at the falling edge of the solar illumination on January 1, 2011. The data logger at Lowry Park Zoo, Figure 9, was accessed on January 11, 2011. Variability due to rapidly changes in cloud cover can be seen in both the Tampa and the St. Petersburg data. The 15-minute solar variation data recorded on the same day at a weather station within 25 miles is shown in Figure 10. Approximately 45% maximum variation in solar irradiance
within 15 minute can be observed, resulting in significant corresponding PV output power variation as well.

It is important to note, however, that the higher frequency variations revealed in the higher resolution data (Figures 7, 8, & 9) should not be confused with the variation or ramping due to solar irradiance variation. In practice, this “jitter” is the result of continuous monitoring [6] and stepped adjustment of the power level by the Maximum Power Point Tracker (MPPT). The MPPT is programmed to locate the optimal relationship of the voltage and current for maximum power output. At lower power levels (less than 20% of the rated power) MPPT struggles to maintain the terminal voltage due to its limited reactive power reserve. In Figure 11, it can be seen that the power factor (PF) is caused to fluctuate as a result of the MPPT algorithm control output commands.

CONCLUSIONS
This paper has taken an initial look at the nature of solar PV variability in Florida, along with an initial look at similarities and differences in the variation in Florida versus that observed in the Southwestern U.S. Seasonal differences in Florida were also examined long with some short-term behavior that a grid-connected PV system exhibits as a result of the intermittency of the solar resource and variation resulting from the PV system power electronics converter and its control algorithms.

Figure 7. St. Petersburg, FL, Albert Whitted hi-resolution PV data (3 second interval)

Figure 8. St. Petersburg, FL, USF hi-resolution PV data (3 second interval)

Figure 9. Tampa, FL, Lowry Park Zoo hi-resolution PV data (3 second interval)

Figure 10. Solar radiation variation recorded at nearby weather radar station

Figure 11. Higher rate of change in Power Factor at low power level (USF St. Pete. Campus)
Significant ramp rates are observed in Florida solar PV output data, attributable to cloud cover variation. In Florida this is significant during the summer months, but, varies diurnally, daily, and seasonally. These data sets are being utilized in analysis of impact on distribution grid voltage control, islanding detection, anti-islanding, protection, and power quality for a variety of grid integration scenarios in Florida utility service areas. That work is in progress and will be reported in future publications.

Future work will more thoroughly examine the short and long-term variation in Florida, seasonally, diurnally, and spatially, and compare this to other locales. Power spectrum analysis will be expanded to aid in determining the periodicity of the data with respect to grid frequency response and protection and control response times. Efforts will seek to determine any limitations in the use of conventional power spectrum approaches and the extent to which other tools, such as wavelet analysis, might be necessary. Findings will be used in simulation-assisted analysis of high-penetration PV impacts on the electric grid.

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